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# THE DEVELOPMENT OF A WEIGHTING METHOD FOR USE IN LIFE CYCLE ASSESSMENTS OF AMINE BASED POSTCOMBUSTION CARBON CAPTURE AND STORAGE (CCS) IN THE ARCTIC REGION

BY
FREDRIK MOLTU JOHNSEN

DISSERTATION SUBMITTED 2017

AALBORG UNIVERSITY
DENMARK

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Dissertation submitted

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# ENGLISH SUMMARY

We presently face a large amount of sustainability challenges. Global warming is often regarded as the most substantial of these, but for instance marine acidification, eutrophication, toxic emissions, land use change, resource depletion, and more are also seen as significant. Carbon capture and storage (CCS) aims to mitigate global warming by capturing, transporting and storing $CO_2$, but the technology can affect other environmental categories, and it is of interest to know more about its environmental performance. In Life cycle assessment (LCA), such categories may be traded off by the methodology's weighting step. A number of LCA weighting methodologies are in current use, but at the inception of the project it was not clear whether the judgment behind their trade-offs is, in lack of a better term, "good".

This project has investigated and provided an answer to the following research questions:

1. In general terms, which categories of facts are of higher rather than lower importance to LCA weighting?
2. What is a high-quality weighting method according to LCA experts?
3. What are the numerical priorities between different environmental impacts in the Arctic environment?
4. In view of sustainability concerns, can an "optimal" weighting methodology be identified?
5. What is the set of weighting factors that can be derived from this weighting methodology?
6. What are the implications for the environmental performance of CCS technology?

The five first research questions have been investigated in five supporting articles. This document outlines their background and cohesion, and details how the accumulated knowledge and results apply to the CCS case.

It is explained how LCA weighting, if it intends to cover a broad spectrum of the environment, will be based on generic estimates at a high level of generalisation. Such estimates do not have to be conjectured by means of human "guesstimates"; a literature survey of weighting and valuation methods in LCA suggested that they can also be estimated from observing the environment itself. The LCA weighting factor set eventually developed was based on the slowness of reversibility of damage to respective safeguarded subjects, i.e. the systems or subjects exposed to environmental insult, expressed in terms of their regeneration time. For both a case of an integrated natural gas-fired power plant with amine based post-combusion CCS as well as for a reference natural gas-fired power plant case without CCS, ecosystem damage caused

by climate change eclipses other environmental impacts provided the weighting assumption made in this project. Preliminary factors identified for scaling LCA results to the Arctic region do not change this conclusion, but these factors should be considered as preliminary estimates, and more research is recommended in order to more elaborately take into account the Arctic environment in LCA studies.

Judging from the results, future LCA studies of CCS could use impact/damage indicators for (A) ecosystem damage, or less precisely (B) global warming potential as proxies for weighted indicators. CCS was shown to significantly improve environmental performance compared to the reference scenario. However, power plants with CCS also cause environmental impacts, and whether “CCS is good” or not cannot be determined in a general sense: it depends on the decision context.

The results reflect the importance of ecosystem damage from global warming. According to the IPCC’s *Fourth Assessment Report*, 4 degrees of warming will commit 40-70% of species to extinction globally. (note that the *Fifth Assessment Report* does not give any such estimate, and that the estimate could understate or overstate the damage potential). Further studies that can provide less uncertain estimates of species extinction from global warming should be a priority in future research. This issue belongs to LCA damage assessment, however, and not to endpoint weighting.

As new species are regenerated only very slowly, this aspect proves so significant that it gives ecosystem and global warming concerns strong priority in the results. It is suggested that earlier weighting schemes may have failed to conclude in this direction because they have been unable to explicitly take into account the slow evolution rate of species.

The development of Arctic scaling factors was not based on sustainability estimates, but on subjective estimates provided by experts. As the range of these factors turned out to be quite conservative, they do not impact the conclusions of the CCS case.

More focus in LCA research can be directed at damage pathways for ecosystem damage, particularly from global warming, as the project finds this dimension to be particularly important. Future LCA studies of CCS may benefit from including long-term storage leakage and rebound effects.

As for the weighting approach developed in this project, it can be explored how it can be combined with other approaches, and whether it can also be used as (or, more technically speaking, be called) a normalisation approach. Moreover, as both the assumptions and the estimates of the weighting method are quite generic in nature, further research that can make conclusions more robust can also be justified.

# RESUME

Vi står overfor store bæredygtighedsudfordringer. Global opvarmning er ofte betragtet som den mest omfattende af disse, men for eksempel marin forsuring, eutrofiering, emission af giftige stoffer, ændringer i arealanvendelse, udtømning af ressourcer, med flere er også set som væsentlige. Carbon-opsamling og -lagring (CCS) har til formål at afbøde den globale opvarmning ved at opfange, transportere og opbevare CO2, men teknologien kan påvirke have negative effekter i forhold til andre miljømæssige kategorier, hvorfor det er vigtigt at undersøge teknologiens samlede miljøperformance. I livscyklusvurdering (LCA), kan de forskellige typer af effekter vurderes i forhold til hinanden ved metodens vægtningstrin. En række LCA vægtningsmetoder er i dag i brug, men i starten af projektet var det ikke klart, om de overvejelser der ligger bag disse vægtningsmetoder var, i mangel af et bedre udtryk, "gode".

Dette projekt har undersøgt og givet et svar på følgende forskningsspørgsmål:

1. Generelt, hvilke kategorier af viden og facts er af højere fremfor lavere vigtighed i forhold til LCA vægtning?
2. Hvad karakteriserer en høj kvalitet vægtningsmetode ifølge LCA eksperter?
3. Hvad er de numeriske prioriteringer mellem forskellige miljøpåvirkninger i det arktiske miljø?
4. Set ud fra en bæredygtighedsvinkel, kan der identificeres en "optimal" vægtning metode?
5. Hvad er det sæt af vægtningsfaktorer, der kan udledes af denne vægtning metode?
6. Hvad er konsekvenserne for vurderingen af CCS-teknologiens miljøperformance?

De fem første forskningsspørgsmål er blevet undersøgt i fem artikler. Dette dokument skitserer deres baggrund og samhørighed, og beskriver, hvordan den akkumulerede viden og resultater har relevans for vurderingen af CCS-teknologi i arktisk kontekst.

Det forklares, hvordan LCA vægtning vil være blive baseret på generiske skøn på et højt niveau af generalisering, dersom intentionen er at dække et bredt miljøbegreb. Sådanne skøn behøver ikke at blive frembragt ved hjælp af menneskelige "guesstimates"; et litteraturstudie af vægtning og værdiansættelsesmetoder i LCA indikerer, at disse også kan estimeres ud fra at observere miljøet selv. Det LCA vægtningsfaktor-set der er udviklet i dette projekt er baseret på den tidsmæssige træghed i reversibilitet af skader, det vil sige systemer eller emner der udsættes for miljømæssig, udtrykt i regenerering tid. Både ved et integreret naturgasfyret kraftværk med amin-baseret post-forbrænding CCS og ved et reference naturgasfyret kraftværk uden CCS, er skader på økosystem forårsaget af klimaforandringer dominerende med

de antagelser der er gjort i dette projekt. Foreløbige faktorer identificeret for skalering af LCA resultater til den arktiske region ændrer ikke denne konklusion, men disse faktorer bør betragtes som foreløbige skøn, og anbefales mere forskning for at mere udførligt at tage hensyn til det arktiske miljø i LCA-studier. Blødere forsknings-tilgange for at undersøge, om Arktis skal være et naturreservat.

At dømme ud fra resultaterne, kan fremtidige LCA studier af CCS bruge effekt/skade indikatorer for (A) økosystemskader, eller mindre præcist (B) potentiale for global opvarmning som stedfortrædere for vægtede indikatorer. CCS-teknologien er vist at forbedre miljøresultater væsentligt i forhold til referencescenariet. Men kraftværker med CCS også forårsage miljøpåvirkninger, og om "CCS er godt" eller ikke kan bestemmes i en generel betydning: det afhænger af beslutningens kontekst.

Resultaterne afspejler betydningen af økosystemskader fra global opvarmning. Ifølge IPCC s fjerde vurderingsrapport, vil 4 grader af opvarmning medføre udryddelse globalt af 40-70% af arterne (bemærk, at den femte vurderingsrapport ikke giver nogen sådant skøn, og at skønnet kunne underdrive eller overdrive potentiel skade). Yderligere undersøgelser, der kan give mindre usikre estimater af udryddelse af arter fra den globale opvarmning bør være en prioritet i den fremtidige forskning. Dette spørgsmål hører dog til LCA skadesvurdering, og ikke til endpoint vægtning.

Idet nye arter kun regenereres meget langsomt, er dette aspekt så betydeligt, at det giver økosystemtjenester og global opvarmning stærk prioritet i resultaterne. Det foreslås, at tidligere vægtningsordninger kan fejlet i denne sammenhæng, fordi de ikke har været i stand til tydeligt at inddrage den langsomme evolution i vægtningen.

Udviklingen af arktiske skaleringsfaktorer var ikke baseret på objektive skøn af bæredygtighed, men på subjektive skøn fra eksperter. Da disse faktorer viste sig at være ganske konservative, påvirker de ikke konklusionerne af CCS casen.

Mere fokus på LCA forskning kan være rettet mod skader veje for skader økosystemet, især fra den globale opvarmning, som projektet finder denne dimension for at være særlig vigtig. Fremtidens LCA'er af CCS kan drage fordel af, herunder langtidsopbevaring lækage og rebound effects.

For vægtningstilgangen udviklet i dette projekt, kan det blive udforsket, hvordan det kan kombineres med andre tilgange, og om det også kan bruges som en metode til værdiansættelse eller til normalisering. Hertil kommer, idet både forudsætninger og skøn i vægtningsmetoden er af generisk karakter, at der er behov for yderligere forskning, der kan gøre konklusionerne og metoden mere robust.

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Supervisors have been Søren Løkke, Aalborg University (Denmark) and Andreas Brekke, Østfoldforskning (Norway) – thanks!

Thanks to everyone.

# TABLE OF CONTENTS

# TABLE OF FIGURES

# LIST OF SUPPORTING PAPERS

Paper I: Johnsen FM (Forthcoming in 2017) The process of handling an excess of complex and interdisciplinary information in a decision support research situation. Submitted for publication: *Interdisciplinary Description of Complex Systems*.

Paper II: Johnsen FM, Løkke S (2013) Review of criteria for evaluating LCA weighting methods. Printed in *The International Journal of Life Cycle Assessment* 13(4):840-849. DOI: 10.1007/s11367-012-0491-y

Paper III: Johnsen FM (2014) Bridging Arctic environmental science and Life cycle assessment: a preliminary assessment of regional scaling factors. Printed in *Environmental Science & Policy* 16(8):1713-1724. DOI: 10.1007/s10098-014-0752-5.

Paper IV: Johnsen FM, Løkke S (Forthcoming in 2017) Weighting in Life Cycle Assessment (LCA) based on externally imposed restrictions: Slowness of reversibility of damage as an indicator of environmental value. Submitted for publication: *Journal of Cleaner Production.*

Paper V: Johnsen FM, Løkke S (Forthcoming in 2017) Weighting in Life Cycle Assessment (LCA) based on externally imposed restrictions: Developing endpoint weighting factors based on regeneration time. Submitted for publication: *Journal of Cleaner Production.*

# CHAPTER 1. INTRODUCTION

This chapter will introduce the wider background for the PhD project, the problem definition, and the research approach.

This project has been an attempt to set explicit, numerical relative priorities to sections of the environment, within the context of the methodology of Life Cycle Assessment (LCA). Such priority-setting belongs to LCA's weighting step. Exploration of weighting and a scramble for well-founded explicit weighting factors forms the main focus of this thesis. If conducted properly, the project would in the process have a chance to provide insight into the unity of the total environment. Immediately note that an inquiry into unity cannot follow from ideologies that uncompromisingly reject any notion of unity, such as, perhaps, atomism or post-modernism. If such unyielding ideologies are assumed, weighting cannot be understood or discussed as a whole.

The background of the thesis is a wider project, "EDeCiDe", which aimed to identify quantitative information on the environmental feasibility of carbon capture and storage (CCS) in the Arctic region. This technology in this region thus forms the case investigated in the project.

To summarise, the recurring questions of this thesis are: Which environmental impacts are more important, and which are less important? How, and on which basis, can this be quantified in the context of LCA, and for the cases of CCS and the Arctic region? The formal research questions are listed in section 1.2.3 below, and some of the topics that are covered are:

(1) To comprehensively circumspect and explore what weighting currently is and, also relevant, what it should be
(2) On the basis of this wide-ranging exploration, to narrow down the problem by making a decision or choice of methodology
(3) To derive numerical weighting factors on the basis of this choice, with a particular focus on the Arctic region and CCS technology
(4) Discuss and conclude

The scope of this PhD project has allowed not only (3) and (4), but also (1) and (2) to be properly developed.

With the conclusion of this brief "introductory introduction", the focus will next proceed to a more thorough presentation of the basic elements investigated in the project: Environmental impact in general, LCA and LCA weighting, and the Arctic region. On the basis of this overview, the research approach and the case will next be presented more in detail.

## 1.1 CHALLENGES AND TERMINOLOGY

### 1.1.1. ENVIRONMENTAL LITERACY

"Environmentalism" is rarely conceived as a long-standing or conservative movement. It is sometimes insisted that current awareness about severe environmental problems in Nordic and Western countries mainly materialised in the late 1960s. However, the largest Norwegian environmental organisation, the Norwegian Society for the Conservation of Nature, was founded already in 1914. Nevertheless, at least in Norwegian public opinion, environmental concern in general is often regarded as some (relatively) new idea which has not yet been fully incorporated in democratic processes, although environmental concerns have been increasingly embraced by societal hierarchies over the last few years.

Regardless of the perceived novelty of environmental concern, different forms of environmental impact have always influenced, imposed boundaries upon, and posed threats to societies – although we have not always been able to perceive all of the relevant interactions. According to Scholz (2011, p. 3), "[m]ost theories on the decline of the Maya and other ancient societies include ecological hypotheses such as environmental disasters, climate change or overpopulation". Historically, environmental impact and damage has been observed, but not always understood. However, well-known examples of historical theories and observations which today would have been connected to the concept of sustainability include that of Malthus (1798/2007), the smog of London (which has been a nuisance since medieval times according to Laskin 2006). There is, and has always been, an intertwined relation between human actions and the environment. When we requires an acceptable outlook on the consequences of human actions, we often need to understand this relationship as fully, as accurately, and, from a practical point of view, as concisely as possible.

It would seem that humanity may seem to have a blind spot for critical environmental issues. Environmental concern in the academic sense is strictly governed by principles and ideas developed in a civilised context. The environment itself, on the other hand, encompasses areas and principles outside the realm of civilisation; it is nevertheless connected to and sustains civilisation. Metaphors from mythology can perhaps help us better understand such principles. If environmental research and civilisation overall as understood in this context is metaphorically speaking connected to, say, the Greek goddess Athene, the wider environment would be governed, by, among others, the deity Pan. It is not obvious whether environmental research has a special status that makes it a medium for the interests of both "Athene" and "Pan", or whether such research should also ultimately be anthropocentric and forward the interests of civilisation itself, and nothing more.

Should nature's influence on man be the only reason why the wider environment has significance, or should we assign the wider environment value in itself? "Paying respect" to the metaphorical character Pan would mean to also embrace uncivilised things. Is it part of civilisation, and with it research, to also embrace filth, and, if so, how can an argument in favour of filth be constructed within a purely civilised context? No matter what the answers are to these questions, if LCA weighting factors move to the core of potential extra-civilisatory blind spots caused by hypothetically excessively refined "civilisation", they may have difficulties to emerge from, as well as to be communicated within, a similarly refined civilised sphere.[1]

A second point connected to the mythological world is that certain narratives concerning the motivation for protecting the wider environment often take the form of avoidance of future tragic outcomes. The tragic outcome in classical tragedy is typically caused by faults in character, with narratives implicitly suggesting moralism as the hypothetical saving grace. Moralism in the Western world, however, is sometimes seen as connected to religion (such as Christianity), which is routinely regarded as unwelcome within most research, and particularly within anything adjacent to the natural sciences. Anything pertaining to negative outcomes should thus be dealt with delicately in research. The choice of arguments and subject-matter when dealing with severe environmental issues needs to avoid being perceived as moralistic, but the researcher may nevertheless have to insist, overtly or not, on a moral cause to retain motivation (or morale).

Sustainability is a key concept in environmental impact studies. The term is, however, of a relatively recent date. There is continuous progress in the scientific understanding of environmental issues, and Steen (2006) and Scholz (2011) suggest that the public has not necessarily yet had the time to develop a correspondingly advanced environmental literacy. The fundamentals of environmental research is to some extent complex, technical and abstract, and thus not always easy for the general public to follow. For instance, if an environmental impact cannot be sensed directly (unlike what the case would be for smog, and that which generally pertains to smell, taste, vision, and noise), there is normally a risk that the general public (and by extension media and politicians) dismiss it as unimportant even if research indicates the opposite. The decades-old string of failures in effectively solving the problem of climate change appears to highlight a dilemma within environmental decision-making: Decisions must to some extent be grounded in the will of voters and consumers, but at the same time they need to be based on established knowledge. What should we do if the two diverge? And should decisions that significantly involve the environment be based on expert opinion, on the stated and observed preferences of the general populace, or simply be left to powerful individuals?

[1] The genre of this document is required to belong precisely to such a sphere, and this has some necessary bearings on the content: what can and what cannot be communicated.

### 1.1.2. ECOSYSTEM DAMAGE FROM CLIMATE CHANGE

The level of damage which is currently being inflicted on ecosystems in general from climate change alone is so overwhelming that it has drawn much attention over the last few decades. Thomas et al. (2004) reported in the journal *Nature* (my emphasis):

> "we predict, on the basis of **mid-range** climate-warming scenarios for **2050**, that **15–37% of species** in our sample of regions and taxa will be 'committed to extinction'. (...) These estimates show the importance of rapid implementation of technologies to decrease greenhouse gas emissions and strategies for carbon sequestration."

The IPCCs Fourth Assessment Report (IPCC 2007a), basing their review on Thomas et al. and a multitude of other studies, concludes (my emphasis),

> "As global average temperature exceeds **4°C** above pre-industrial levels, model projections suggest **significant extinctions (40-70% of species** assessed) around the globe."

The Fifth Assessment Report, however, does not include this numerical estimate, perhaps because of the uncertainty in the final estimates. Nevertheless, it is obvious that damage to ecosystems is about to destroy a lot of things that were a long time in the making.

Scientific or academic discourse may not be a perfect vehicle for normative discussions, but it should be uncontroversial to claim that the above provides a normative incentive of some magnitude. Solely on the basis of the estimates in the two quoted passages, it is difficult to disagree with the recommendation of Thomas et al. (2004) to implement carbon sequestration rapidly, or perhaps even as fast as humanly possible.

### 1.1.3. LIFE CYCLE ASSESSMENT (LCA)

Provided that the above information is accurate, the problem must simply be fixed, and as soon as possible. There does not seem to be any time for worry over academic detail and the scientific "fine print": Every moderate problem which can arise when, say, carbon sequestration is implemented cannot be taken into account if there is little time, and, some would say, at least not if it reduces our motivation to "save the planet", so to speak. The current procrastination in dealing with anthropogenic climate change is on course to realise certain strongly undesirable environmental and social scenarios, as described e.g. by Lynas (2008).

The decision-making of social hierarchies is more often than not based on a broad analysis of consequences. Life Cycle Assessment (LCA) is a (mainly) quantitative methodology for environmental assessment, which at least to some extent has been standardised by ISO 14044 (ISO 2006). ISO 14044 in turn cites the still relevant older standard ISO 14040. In LCA, the assessed process or product is seen in a wider perspective, as part of a whole product system, for instance from raw material extraction to the production phase to waste management. In this case, emissions and impacts are registered and added "from cradle to grave". Hence, an LCA of a mobile phone would take into account for instance the impact of the extraction of the metal it contains, as well as impacts related to all expected phone calls and the disposal of the phone – and more. With the use of databases such as Ecoinvent (Wernet et al. 2016), the resulting model of relevant inputs and outputs can end up as very complex and wide-ranging. The wider methodological picture is also intricate; see *e.g.* Baumann and Tillman (2004) or the numerous and voluminous guidelines assembled under the umbrella "The ILCD handbook".[2]

Hence, an LCA study investigates the consequences of a broad collection of interrelated[3] human actions. In addition, LCA studies normally assess a broad array of environmental consequences, not only climate change. Emissions that cause anthropogenic global warming normally constitute only a fraction of the list of

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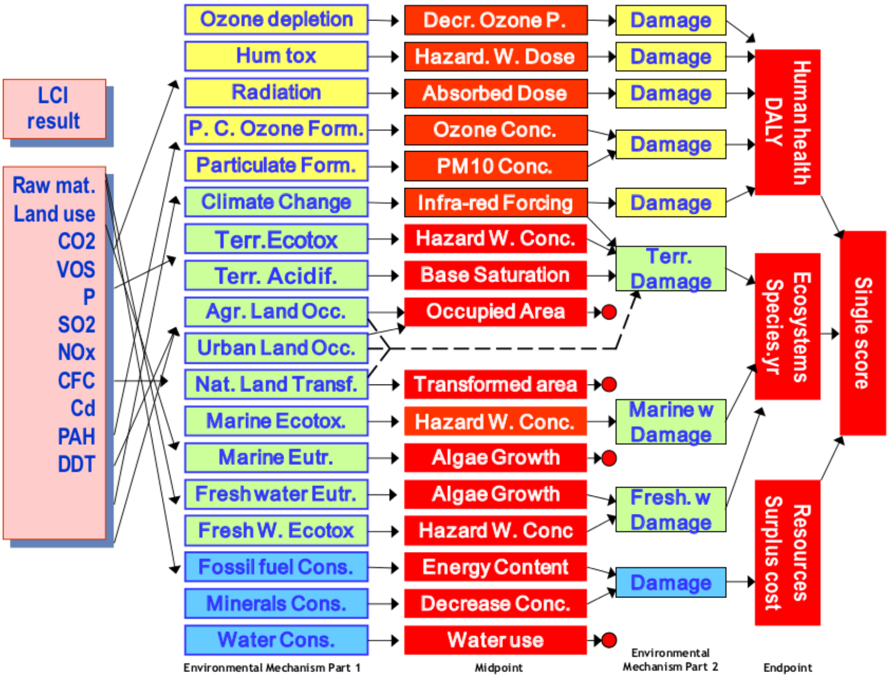
[2] Whereas standards and best practices are available, there are nevertheless methodological differences between LCAs. Two alternatives are "attributional LCA" and "consequential LCA". The technical differences between these approaches are outlined by Schmidt (2008). Consequential LCA replaces some of the accountancy features normally found within LCA with prospective economic modelling approaches, in a bid to increase the environmental realism of the modelling (Earles and Halog 2011). Normally sorting under the consequential LCA umbrella are direct and indirect rebound effects (Earles and Halog 2001, p. 448; Weidema 2008). For instance, a decision to increase airplane production may cause lower prices on airplanes and subsequently a larger demand for and use of airplanes and air travel. The increase of air travel is a rebound effect, and in turn causes environmental consequences which can be quantified and counted in an LCA study. Rebound effects (a synonym term is take-back effects) differ from *side effects* in that they do not follow from causal necessity, but from causal tendency (see *e.g.* Anjum and Mumford 2010). Such effects are normally not quantified in LCA studies; they do, however, form part of the discussion chapter below.

[3] The point of convergence of these actions is the "functional unit", which needs to be defined near the start of the LCA study. The functional unit could for instance refer to an industrial output which serves to clearly define the investigated product system. As an example, the functional unit of an LCA of a particular mobile phone could be one produced unit of this phone, or even one phone call. The calculated environmental impact will in turn relate to this unit.

emissions, “LCI results”, assessed in an LCA. In the Life Cycle Impact Assessment (LCIA) phase of LCA, all the different emissions modelled are grouped according to their calculated impact on the environment (into the “midpoint” or impact categories). Next, these impact indicators are sometimes grouped according to the tangible forms of damage that they produce (“endpoint” or damage categories). This framework is carefully outlined by the ISO 14044 standard (ISO 2006), but there are individual and competing LCIA characterisation methods, which may use quite different sets of impact and damage categories, and their characterisation methods as well as weighting when it is connected may also be different.

Perhaps the most recognised of these LCIA methods is the ReCiPe 2008 LCIA methodology (Goedkoop et al. 2013). Its structure is outlined in figure 1. Climate change is included, as well as ozone depletion, human toxicity, radiation, ozone formation (“summer smog”), particulate formation (such as $PM_{10}$), terrestrial ecotoxicity, terrestrial acidification, agricultural land occupation, urban land occupation, natural land transformation, marine ecotoxicity, marine eutrophication, freshwater eutrophication, freshwater ecotoxicity, fossil fuel depletion, mineral depletion, and water depletion. We can observe that damage to ecosystems from infrared forcing, which in the above was suggested to be of potentially existential importance, forms only a small part of the scope of LCIA, at least as it appears from the figure. As global warming is likely important whereas some of the other categories may likely be less important, the suggested relative importance of weight of global warming and the other categories somehow needs to be better reflected by LCIA as a whole than by figure 1.




# Figure 1. The structure of the ReCiPe 2008 LCIA methodology, from the methodology's documentation, Goedkoop et al. (2013, page iv)[4]

The calculation of ecosystem damage (damage characterisation) from the infrared forcing in ReCiPe is based on the article of Thomas et al. (2004) above (Goedkoop et al. 2013, p. 21). If this damage is more important and pronounced than all the others, one would expect it to simply dwarf other indicators in most LCIA calculations. Hence, it would seem that LCA anyhow cannot understate the effects of global warming. However, there are three damage categories, not one: in addition to ecosystem damage, human health and resource depletion are also considered. What are the "correct" relative weights of these categories? If one ponders this question for some time, it may become clear that this is a question of immense scope. Hence, it would seem that in order to finally be able to conclude numerically whether

[4] *A side note is that the description of ReCiPe in European Commission JRC (2010, p. 43) appears inconsistent with the method's documentation, as it claims "PDF x m$^2$ x yr" to be the unit for ReCiPe's ecosystem damage. Hauschild et al. (2013, p. 689, table 2) repeats this. Slay (2010, pp. 5-6) outlines the relation between the relevant units.*

technologies for carbon sequestration are required from a total environmental outlook (which would require a comparison of "single scores" to the right in figure 1), one first has to solve this comprehensive or perhaps even impossibly complex puzzle. As pointed out above, this exercise is, despite its complicated nature, the object of this thesis. The background is that from the point of view of the EDeCiDe project through which this PhD project was financed, there was a perceived need to clarify, in particular, whether human health impacts from toxicity were more important or not than global warming impacts for the CCS/Arctic case.

This leads us to the key term of this thesis. Assigning relative weights in order to trade off midpoint or endpoint scores is called *weighting*. Weighting in an LCA context is sometimes called *valuation*.

As LCA weighting is the key concept in this thesis, some background and context is required. The somewhat cumbersome definition of weighting in ISO 14044 is

> (...) converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices" (ISO 2006, section 4.4.3.1)

The scope of LCA weighting is less clear. An investigation was previously made by Bengtsson and Steen (2000). They recommend that weighting should only be regarded as

> (...) a test of the compatibility between environmental impact profiles and different value profiles rather than as a procedure leading to a true measure of the aggregated impact

If weighting makes no claim to be a "true measure", however, any final, weighted recommendation based on LCA can only be regarded as a subjective opinion. However, if everything is merely left up to subjective opinion, one can just as well simply claim that carbon sequestration should be implemented as fast as possible, regardless of any LCA calculation – or the opposite. Hence, the recommendation of Bengtsson and Steen seems somewhat unambitious. One would expect significant decision support to have some degree of firm ground, e.g. empirical data which is not only based on opinions or socially constructed truths. It can be observed that quite a bit of methodological scrutiny has been involved in the design of some of the existing weighting schemes, presumably in order to make them provide as high quality trade-offs as conceivable (Ahlroth et al. 2011). The idea that truth is merely a social construction and that empirical data from the physical world is usually more or less irrelevant is perhaps not uncommon in some social sciences, and perhaps it is thus due to the disciplinary background of the author that this track has not been followed in this project. Whenever the "quality" notion, or any similar notion that suggests a hierarchy ranging from good to bad emerges in a scientific discussion, however, there is a risk that the scientific treatment will degenerate into degrees of lofty moralism.

Any appeal to aim for higher quality than well-intended opinions of fellow humans will easily appear haughty and arrogant, and any scheme that aims for higher-quality information than this thus needs to be quite elaborate.

Whereas the scope of weighting thus remains to be investigated, how weighting relates to the architecture of the LCA methodology can be explained. First, the very term weighting can be defined in a number of distinct ways, depending on methodological choice. A *normalisation* step may be involved immediately before the weighting (Finnveden et al. 2002). Normalisation "transforms an indicator result" [i.e. midpoint or endpoint result] "by dividing it by a selected reference value" (ISO 2006, section 4.4.3.2.2). Typically, a normalised acidification result has been divided by the total amount of acidification globally or in the region per year, and so on for the rest of the categories. This leaves dimensionless, normalised indicators which describe the fraction each impact indicator from the functional unit of the product assessed makes when compared to each total emission in the region. Next, these dimensionless fractions can be weighted in relation to one another.

Hence, there are four fundamentally different approaches to weighting: midpoint weighting and endpoint weighting, which both can be divided into weighting after normalisation and weighting without any prior normalisation. As pointed out above, the key underlying factor is to weight in an ethical manner, but as will be explained, a goal was also to approach an "objective" or "quasi-objective" principle for weighting. The former of these goals implies that we are approaching weighting more than normalisation, but the latter goal suggests that we are actually closer to normalisation than to weighting. As the "ethical" part was continually regarded as the most important aspect in this project, the term "weighting" is used throughout, as it is weighting, not normalisation, that pertains to the "valuesphere". However, this terminology is admittedly a matter of taste: a less strong underlying focus on ethics might have justified the use of the term "normalisation". As the weighting conceptualisation involved searching for an appropriate indicator or estimate of "value" of different parts of the environment (in ethical terms, not necessarily monetary terms), the term "valuation" is also used. The slight lack of precise overlap with terminology arose because an aim for good trade-offs was seen as more important than conforming very precisely to existing terminology from the start. Notably, insisting on a very strong divide between weighting and normalisation was found to not be a fruitful approach in this case. The terminology problem comes up the supporting papers and in the suggestions for further research in this thesis (section 6.12).

The hypothetical total environmental impact which can be calculated by means of weighting factors is eventually a deciding factor in *classification*, *i.e.* the choice of midpoint and endpoint categories to include in LCIA. For instance, if glacier melt were considered to be a very important environmental category, it could be explicitly included among the endpoint categories of figure 1 (of course, related to the global warming midpoint). If important categories are left out of LCA, or if key environmental mechanisms are insufficiently, erroneously or not at all mathematically *characterised*, LCA results will be deficient. Along with the potential for omissions in the life cycle inventory (LCI) phase, this gives LCA "blind spots" which are difficult to assess without a creative mindset. Examples in typical current LCA studies may be certain toxic effects, marine effects as well as social impacts.

As pointed out above, characterisation in LCA is not fully standardised, and relies on a number of methods that have evolved gradually. Established LCIA methods with final weighting, such as ReCiPe 2008, have been developed over decades, but somewhat crude approximations and assumptions are nevertheless made in characterisation modelling. As a general rule, the further to the right one moves in figure 1, the more uncertain the assumptions, estimates and results.

As demonstrated, the dilemmas of LCIA converge within the weighting step. Weighting has a potential to ease and improve the interpretation of LCA results; however, its simplicity also poses a risk. If a decision for example on the environmental desirability of an item is based solely on a superior single score, but the weighting is performed in a completely misguided manner, then the whole LCA study has essentially been in vain or it can be counterproductive. Avoiding weighting is one tempting alternative, but as shown above, it may tacitly give the impression that each category carries more or less equal weight, or LCA reports can be designed to give the impression that one category (e.g. global warming) carries more or less all weight. This is not necessarily desirable. Not weighting may also give the impression that the categories are incomparable thus introducing a stalemate-like indecisive situation with an overload of information.

Finally, it can also briefly be pointed out that ISO 14044 (ISO 2006) states that:

> "Weighting steps are based on value-choices and are not scientifically based."

On this background, the standard recommends that weighting is "*an optional element*" – it can be omitted or included in LCA according to the preferences of the LCA practitioner. It should also be noted that aggregating everything to a single score for the product or process which is analysed by the LCA is one of two uses of weighting. It can also be used for "converting indicator results of different impact categories by using numerical factors" (ISO 2006, section 4.4.3.4.2), i.e. for the purpose of comparing impact/damage categories or indicators without proceeding to the final aggregation of these indicators into one single score. An example of how all of this translates into practice is provided by the case of Chapter 3.

### 1.1.4. SITE-SPECIFIC LCA AND ARCTIC ENVIRONMENT

LCA calculations are generally site-generic. However, this means that LCA results will not necessarily reflect the impacts and damages actually caused by a particular emission. In response to this, it is possible to make LCAs spatially explicit, *i.e.* more relevant to a certain region.

Potting and Hauschild (2006, p. 12) describe three suggestions for levels of spatial differentiation within LCA:

- **Site-generic** spatial differentiation, where all sources "*are considered to contribute to the same generic receiving environment*"
- **Site-dependent** spatial differentiation, where "*some spatial differentiation is performed, by distinguishing between classes of sources and determining their subsequent receiving environment*. (...) *The receiving environment is typically defined at high spatial resolution (scale at maximum 150 km, but often down to a few kilometres)*"
- **Site-specific** spatial differentiation, which is a "*very detailed spatial differentiation*"

Site-specific assessment is normally outside the scope of LCA as a whole. Site-dependent assessments, on the other hand, are often outside the scope of LCA studies, but there is nevertheless a significant number of peer-reviewed articles on site-dependent characterisation. For instance, an article by Boulay et al. (2011) develops regional LCA characterisation factors for human health damage from freshwater use. In comparison, this PhD project aims to cover not only one, but all relevant environmental mechanisms, and will primarily focus on weighting, not characterisation.

In an international workshop for the project EDecIDe, freshwater use was highlighted as potentially one of the most regionally contingent impact categories: Some places water is a scarce resource, but in some areas it is decidedly not. Most classes of environmental impacts are non-global in scale, and the regional dimension is thus important – and, not much inquiry has been made into how LCA and LCA weighting should relate to the Arctic region in general. The Arctic is perhaps known as a pristine, wild, isolated and very sparsely populated environment with polar bears. However, its more southerly parts do not consist of polar desert, and the real picture is somewhat more diverse.

In environmental terms, the region has an obvious link to global warming. As mentioned in section 1.1.1, the public impression of an environmental impact is to some extent determined by what can be sensed directly. Greenhouse gases are normally invisible, and global warming takes place so slowly that it is not immediately noticeable. Hence, changes to the Arctic cryosphere, such as ice and snow melt, are at least to some the most immediately obvious and visible changes globally that result from climate change.

What is less obvious to the public is that the warming in Arctic areas is also much more pronounced than elsewhere on the planet in terms of temperature increase. This is due to albedo effects, *i.e.* a darkening of the Earth's surface when snow and ice melts. According to the IPCC (2007b):

> "Arctic climate is characterised by a distinctive complexity due to numerous nonlinear interactions between and within the atmosphere, cryosphere, ocean, land and ecosystems. Sea ice plays a crucial role in the arctic climate, particularly through its albedo. Reduction of ice extent leads to warming due to increased absorption of solar radiation at the surface."

However, whereas climate change and its effects are of crucial importance to the Arctic (ACIA 2005), this problem is of course not primarily due to anthropogenic emissions in this region itself. Concentrations of $CO_2$ and other greenhouse gases in the atmosphere are increasing globally. It is primarily regional *conditions* (such as the prevalence of ice and snow), not regional *emissions*, that contribute to the adverse observed warming. Due to the very long residence time of $CO_2$ in the atmosphere, it does not really matter from where it is emitted (at least not as long as it is emitted to air).

This illustrates how the Arctic can be approached in two fundamentally different ways in an environmental assessment. First, actual impacts and damage that are known to take place in the region can be *monitored*. Here, "climate change" is evidently more pronounced in the Arctic than elsewhere. Second, the actual impacts and damage caused by specified emissions and interventions in the region can be calculated. The latter is the primary object of LCA. Following the logic above, when for instance an industrial source in the Arctic is the source of emissions, climate change is not necessarily more important than when the source is situated in another region. Hence, "climate change" is readily *observed* in the Arctic, but it is not necessarily more readily *caused* by emissions to the Arctic region. Before actual environmental priorities in the Arctic region can be made, it is necessary to understand that the term "climate change" can refer to two rather different phenomena in the two examples; it is ambiguous.

The subtle difference between monitoring and impact assessment is highlighted by the name of the *Arctic Monitoring and Assessment Programme* (AMAP). This is one of several related organisations organised by the Arctic Council, and since the 1990s it has released environmental assessment reports on the Arctic region. It is a significant umbrella organisation for Arctic research: AMAP's comprehensive 1998 assessment report was 869 pages long and involved "*over 400 scientists and* *administrators*" (AMAP 1998, p. vii). In agreement with the scope of LCA, AMAP assessments characterise and document a diverse range of environmental impacts and damages, not only climate change. They may thus serve as a basis for comparisons between Arctic environmental science and LCA. In addition to AMAP's assessment reports, an abundance of independent scientific articles on the Arctic environment are continuously published, as well as, at the national and subregional level, reports made by governmental bodies, businesses, NGOs and consultancy agencies. The report of Ottersen and Auran (2007, in Norwegian) is one example of a comprehensive report from outside the sphere of journal articles.

LCA weighting involves a brief numerical summarisation of the environment, but due to the large amount of available information, it is challenging to succinctly summarise the key topics within the Arctic environment. Nevertheless, a few aspects can be emphasised in this introduction.

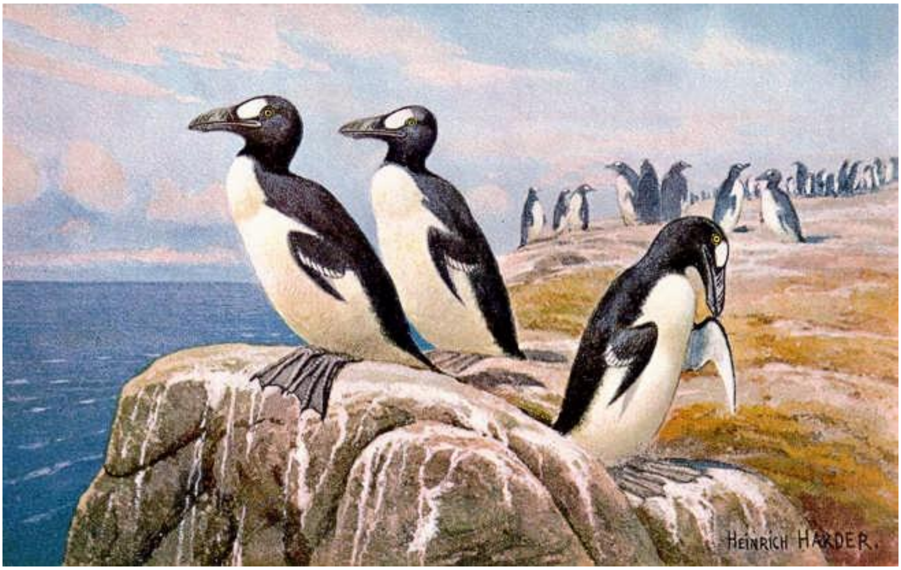



**Figure 2. The bird originally called "penguin" (Great auk, Pinguinus impennis) inhabited the North Atlantic/Arctic region. It went extinct c. 1850 due to human interference. The Antarctic penguin was named after this bird due to its outward similarity.**

Arctic terrestrial biodiversity is relatively low, but the Arctic is nevertheless sometimes referred to as particularly vulnerable to environmental impact. Now, *high* biodiversity, such as that found in the Amazon rainforest, is often linked to higher vulnerability, so what makes the Arctic perceived as particularly vulnerable? Perhaps part of the answer lies in what makes a habitat uninhabitable to plants. Dickinson and Murphy (1998/2007, p. 34) summarise this very simply: “Stress *high*, disturbance *high* --> Plants *excluded*” (their emphasis).[5] They continue, “Plants do not appear capable of exhibiting *simultaneously* (i.e. in the same phenotype) sets of traits for tolerance of *both* high stress and high disturbance” (their emphasis). This does not only refer to static observations of ecosystems, but also to impact assessment: “A combination of high stress and high disturbance is one way to destroy or indeed prevent the occurrence of a functioning ecosystem”. Hence, Arctic plants under high stress cannot be subjected to much anthropogenic disturbance, and Arctic plants under high disturbance cannot be subjected to much anthropogenic stress.

Although there are subregional variations, marine life is generally speaking abundant in the Arctic compared to terrestrial life. Some of the vulnerability of marine life comes in part from the particularly long food chains found in the Arctic marine ecosystems (AMAP 1997, p. 48). This makes bioaccumulation/biomagnification of toxins particularly harmful, and this adversely affects the top predators both in the sea and on land: large birds as well as mammals, including humans. As for instance mercury levels in human populations across the Arctic are already above acceptable or safe levels (AMAP 2011, p. 30), it can be argued that no further emissions and industrial activity than that seen today can take place in the Arctic, because the region simply cannot support it.

If one unvarying regionally specific LCA is to be devised for the whole of the Arctic region, its resultant spatial resolution would be significantly lower than what Potting and Hauschild (2006) defined as “site-dependent”. The Arctic can be divided into diverse ecoregions of particular environmental relevance – examples of divisions are found in figure 3 and e.g. WWF’s report “The Global 200” as well as Olson and Dinerstein (2002). As Arctic ecoregions are quite different from one another, considering the Arctic to be one *uniform* whole will lead to an incomplete picture. Nevertheless, spatially explicit LCIA modelling in which the Arctic is seen exactly as a whole provides an improvement in comparison with a global, site-generic approach where the specificity of the region is not taken into account at all.

[5] Dickinson and Murphy (1998/2007) define stress as “any factor which tends to reduce the efficiency of functioning of one or more key physiological processes in the organisms occupying a given ecosystem” (p. 77). They define disturbance as “any influence on an ecosystem, which increases the probability of destruction of biomass of the organisms present” (p. 92). Disturbance refers to mechanical influence or cataclysmic events (such as grazing and fires), whereas stress rather refers to sub-optimal physio-chemical conditions (such as lack of sunlight and nutrition, saltiness of available water, drought, etc).

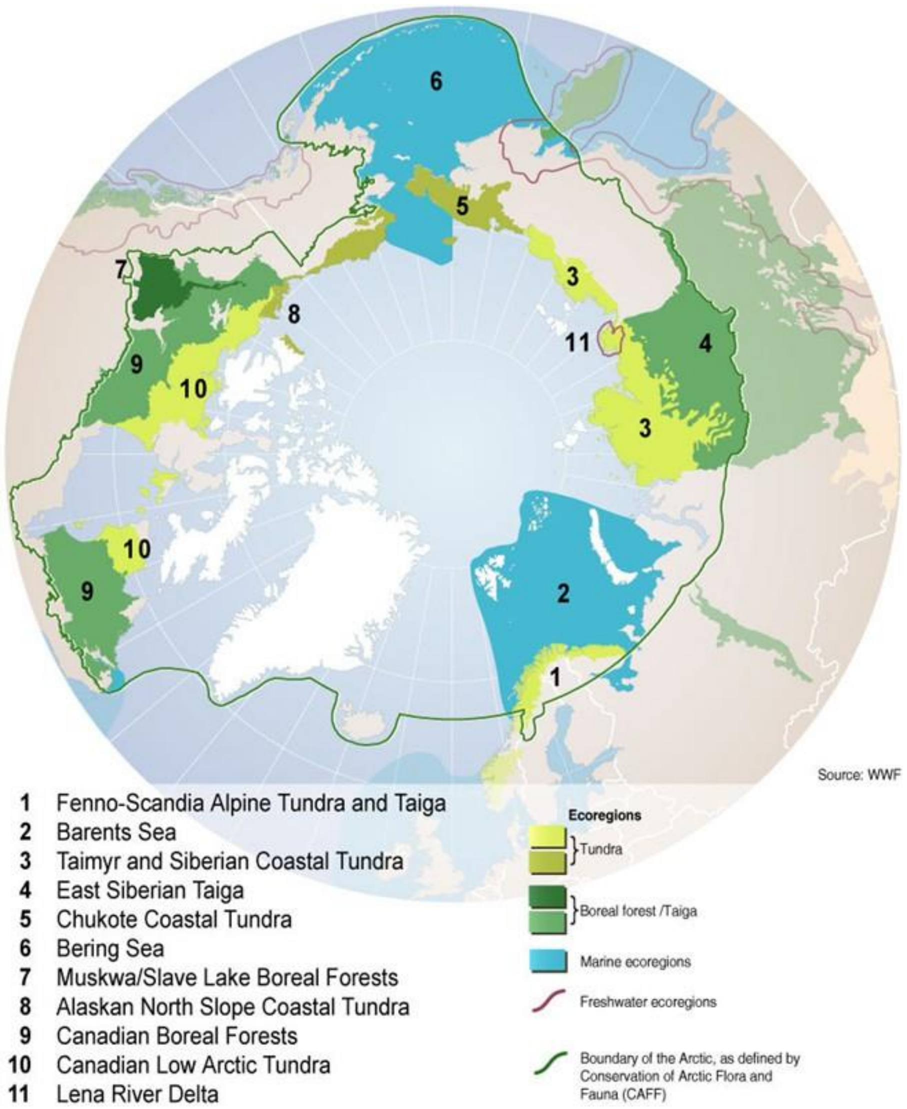



Figure 3. Ecoregions in the Arctic, as proposed by WWF. This PhD project considers the Arctic as a whole, which means that any difference between ecoregions is not considered. Map by Hugo Ahlenius, UNEP/GRID-Arendal (GRID/UNEP 2006). Used with permission

.

With terms involved in LCA, weighting and the Arctic thus briefly introduced, section 1.2 introduces the problem definition of the project.

## 1.2. DEVELOPMENT OF RESEARCH QUESTIONS

The research approach of the PhD project was briefly outlined in the beginning of chapter 1. The present section will contemplate how the particular nature of and complexities of the subject-matter during the course of the project led to specific research questions. An extended presentation of the research questions of in the project are presented at the end of the section.

The identification of a somewhat stable methodological ground for weighting forms part of the scope of the project. This proved to be challenging, as a meta-methodology for identifying a weighting methodology is thus required (and a meta-meta-methodology for discussing or validating this meta-methodology, *etc.*) This required the project to take on a somewhat philosophical nature. During part of the project, the issues that had to be wrestled with were of a normative character. Such issues are almost by definition difficult to deal with, and even document, in the objective and reproducible manner which is normally perceived as suitable for an academic or at least a scientific publication.

The fields of industrial ecology and life cycle assessment are ostensibly transdisciplinary, multidisciplinary and/or crossdisciplinary, but in practice they are pervaded by an engineering and natural science spirit. It appears that the simplest, most tool-like, and most down-to-Earth answer is often perceived to also be the best answer. Most journals connected to this field avoid too lofty discussions – metaphysical mediation between normative positions does not fit well into such contexts, so the rule is rather often to *describe* or *assume* normative positions and leave it with that. This form of paradigm is useful as nobody gets carried away and as contention is avoided, but it may lack some of the creativity that one would expect within a transdisciplinary field. With the significant normative challenges that LCA weighting involves, the complexity of Arctic ecosystems, and the uncertainties involved in LCAs of CCS, a too case-specific perspective and a lack of normative discussion can be questioned. Disciplinary "tunnel vision" was criticised for the case of a sustainability context by Næss (2010). If something is complicated, is it truthful to eventually describe it as simple? Funtowicz and Ravetz (1994) makes some of the same criticism: numbers are typically interpreted as something precise and reliable, but in interdisciplinary or interparadigmatic science this is actually not normally the case. It is almost as if the razor-sharp clarity that can be provided by numbers and neat diagrams in extremely interdisciplinary efforts should be avoided, or at least not be considered the only guiding virtue.

Of course, the purpose of this document is primarily to *clarify* the project's processes, findings, conclusions, *etc.*, but it cannot be complete without some further *clarification of the confusion* that was perceived during the course of the process. Among other things, it is necessary to clarify a general answer to questions of the type "but, why did you not consider..." Such questions are particularly troublesome to weighting: as it is not only a scientific but also an ethical question, there is an overabundance of subjects that to some extent and at some level can be of relevance. The doubts expressed over the following two sub-sections could perhaps be perceived as somewhat redundant to the overall narrative of this thesis. Impatient readers might want to immediately move on to the research questions in section 1.2.3, but will in that case run the risk of not understanding some of the implications involved.

### 1.2.1. THE COMPLEXITY OF LCA WEIGHTING

A PhD project is of necessity at the forefront of some academic and scientific inquiry, paving new intellectual ground and providing some novel factual knowledge. One important problem with the concepts of "weighting" and "the Arctic environment" when they are considered in general terms, is that the ground which each of them aspire (or should aspire) to cover is so large that aiming for the vanguard of every scientific topic relevant to them is too challenging.

The proportions connected to the movements of celestial bodies, or what was at some stage called the "music of the spheres", was eventually uncovered by Copernicus, Brahe, Kepler, Newton and Einstein. This could be achieved with accuracy and confidence, because the movements of large bodies in the solar system, when assumed to be void of intelligence and a will of their own, turned out to be relatively simple. An ethical inquiry into the environment, however, is more complex. Although there might be a unifying structure, harmony or mathematically decipherable "music" somewhere in the environment, it would involve life, being and complex micro-scale and large-scale systems, and not mere movement of obvious, well-defined and material bodies.

The classical and obvious analytic method in scientific projects is to demarcate smaller problems within a larger field of study, by starting from more or less informed assumptions and hypotheses. In this way, light can be shed on a very narrow topic, and the PhD candidate can eventually claim to be a leading expert, although only within a very tiny subset of global research.[6]

However, in this particular project, this strategy would appear to be unacceptable. As a starting point, the total environment is complex, with no obvious unifying features. Finnveden (1997) explains how LCA weighting is not merely a scientific or academic undertaking, but also a task where ethical questions enter the picture - the trade-offs of weighting require that fundamental value-laden choices must be made, either tacitly or explicitly. Fairness and impartiality concerns may also enter the picture, and science is not necessarily the best vehicle for dealing with such issues. Yet again, figure 1 is relevant: The scope of LCIA is to evaluate damage to human health, ecosystems and resources. The scope of weighting, then, is to evaluate how important human health, ecosystems and resources are in relation to each other. This not only evokes a number of unusual questions: what is the value of animals in relation to the value of individual humans? To which extent do we need to care about future generations? It also becomes clear that a poor choice of weighting factors may have bad consequences in the real world. The project is thus not just an academic game. The subject needs to be approached with corresponding foresight and carefulness, and assumptions and delimitations in scope cannot always be made just because they are simple, practical and lessen the researcher's workload.

With LCA weighting, all the LCA data which has been gathered and calculated is ultimately connected. This connection can hypothetically be performed in view of the total environment, the wishes of the LCA commissioner and LCA experts, societal factors and needs, future scenarios, ethics, opinions in general, policies, psychology, law, philosophy, ontology, epistemology, perhaps theology... etc. In this project, the "everything" that apparently could and maybe should be covered by weighting factors needs to be reflected only by a tiny and consistent set of numbers. The conciseness of the information held within these numbers must thus be very high: only a few numerals need to contain an extreme amount of relevant information.

Simple numerals that estimate a particular fundamental feature of otherwise puzzlingly complex systems are an integral part of LCIA, and are often called

[6] There are many ways of explaining this point. One is that Cartesian dualism, which forms the fundament or even the worldview of science, makes one basic assumption: it separates "matter" from "spirit" (without denying the general relevance of the latter). The ensuing inability to analyse matter in conjunction with life, however, in practice leads to a materialistic worldview in which consciousness, being and ethics cannot take part. In other systems of thought, perhaps notably Thomism, matter and spirit are fundamentally interweaved, which in turn makes ethics an intrinsic part of material analyses. This allows an entanglement of ethics and science. At the same time, however, this eliminates the independence and neutrality of science, and lets moral dogma pervade everything. As this is normally undesirable, ethical considerations and other holistic notions are usually relegated to discussion points in scientific research.

indicators. In order to develop concise weighting factors, some process of simplification or estimation must take place. If this is done carefully, the numbers can become deceptively, not actually, simple, thus “indicating” something significant but normally unseen.

This illustrates some of the demarcation problems inherent to weighting and a search for indicators in general. If the subject-matter demands a holistic stance, this means that you cannot really make any assumption or demarcation of the problem without also committing an *error*. What is worse, the eventual result could ultimately be an effect of the initial assumptions made. This would leave weighting to be, essentially, a measurement of choices made during the research process, and this would not necessarily lead to reproducible or scientifically justifiable results. A claim that a set of weighting factors is overly sensitive to initial assumptions is also a claim that it aims to identify indicators within what essentially is a chaotic system (Gleick 1987). Now, some systems that appear chaotic from the inside could in reality be governed by homeostatic processes at a higher level (see for instance Von Bertalanffy 1969, pp. 160-163, 210-211) – and the mechanism of such processes could be relevant to weighting. If so, one would have to understand how certain large-scale homeostatic systems work.

Now, one obvious research strategy would be to simply accept seemingly inoffensive assumptions made in previous research. Several different LCIA and weighting methods exist; an updated and comprehensive overview is given in the ILCD handbook (European Commisson JRC 2010). At a methodological level, two different taxonomies are provided by Ahlroth et al. (2011) and Huppes and van Oers (2011). As shown by Ahlroth et al. (2011), different weighting methodologies stem from different academic disciplines. In choosing one of them, the weighting scheme can be criticized for favouring or putting too much weight on one particular discipline. A more comprehensive approach would be to mediate between different approaches. However, mediating between academic traditions is challenging, as they may hedge different values (Berggren et al. 2009), or it can take on a seemingly quite arbitrary character, such as in the meta-weighting factors proposed by Huppes et al. (2012). A long-standing problem is also that such mediation, for instance through metaphysical or philosophical investigations, may lead to excessive sophistry, as criticised by Al-Ghazali (1100). One particular problem which can be highlighted is that the field of decision theory (game theory, rational choice theory, *etc.*), which could have been connected to the decision or choice of weighting factors, more often than not assumes that a “rational” decision is one which maximises personal gain. This is to some extent in exact discord with the normative ethical theory of Aquinas (1274/1948), in which charity (*caritas*) is claimed to be, as it were, the meaning of life and the ultimate cause of happiness. If we accept both the academic disciplines behind these two contradictory ideas, we may end up with inconsistency.

In sum, the observations of this subchapter are intended to serve as a warning to readers: Even if weighting factors are somehow available, even in peer-reviewed journals or in a PhD thesis, this does not automatically imply that their use is justified or uncontroversial. A fundamental assumption made when proceeding with this document is that the numerical approach to environmental assessment of both LCA and LCA weighting is ethically, environmentally, socially, and scientifically warranted. A provision for this is that those who eventually are given, and make decisions based on, LCA results based on weighting possess a minimum of wisdom and/or common sense. LCA and similar tools can provide decision support, but not orders.

### 1.2.2. THE COMPLEXITY OF THE ARCTIC ENVIRONMENT

Whereas LCIA and weighting may come across as startlingly complex topics, they are nevertheless man-made constructs. The Arctic environment, on the other hand, can perhaps be said to exist independently of human perception: it is a *ding an sich* (or *thing-in-itself*, see Kant 1781/2013) which in turn can be conceived, classified, and characterised by humans in a large number of ways.

Now, due to the limitations of the human mind, our perception of the Arctic region must at all times be somewhat restricted – a similar point is also made by Steen 2006). This may beg the question of whether there is any *general* pattern to conceptions about the Arctic environment at all. Ecosystems are notoriously difficult to understand and characterise (as outlined by for instance Kay et al. 1999), and a systems approach cannot really capture the subjective, phenomenological dimension experienced by for instance mammals and birds in the region. It was shown in section 1.1.4 that the Arctic is not a homogeneous region. Moreover, even its definition is not clear-cut. Also, the cognitive ability of some of the region's large mammals, such as whales, is unclear. If they are sentient and intelligent, this could necessitate a more specific assessment of damage for these species. At the same time, some will always insist that an anthropocentric perspective should be retained.

Part of the Arctic is inhabited by people of what can be classified as traditional cultures (*e.g.* some Sami, Inuit and Norwegians), but also by industrialised (or post-industrialised) peoples such as *e.g.* city-dwelling Americans and Russians; the divide is not necessarily definitive. Conceptions and opinions about the Arctic environment vary between traditional cultures and city-based societies, and a trend within Arctic research is to be unwilling to deny or ignore the understanding of nature held by traditional peoples, see *e.g.* Berkes (2012). This may to some extent challenge the authority of for instance natural scientists in the region.

Worldviews relevant to environmental outlook in general appear to vary significantly across countries and between individuals (Hofstetter 1998, ch. 3; Grendstad et al. 2006). In addition, Arctic and international environmentalists, as well as scientists/experts, may have a somewhat different outlook than others on the environment. Tourists to the region form another group that could have a particular outlook, for instance regarding the importance of aesthetic values. Finally, LCA commissioners may have their own opinions on what is and is not important about the Arctic.

Whereas most of these groups would probably accept the basic observations in AMAP's environmental assessment reports (see section 1.1.3), the sum of these reports provides a very comprehensive body of information. There could be different interpretations with regard to which pieces of information are more important.

Traditional cultures in particular sometimes hold fundamentally different worldviews (sometimes summarised as Traditional Ecological Knowledge, TEK; Berkes 2012). TEK may be puzzling (as well as illuminating) to those perfectly socialised into "regular" environmental science. For instance, as outlined by Berkes (2012), spirituality and sacredness often play integral parts in traditional environmental understanding. For context, an influential article by White (1967) suggested that the ecological crisis in Europe began with the destruction of Pagan animism and its taboos against intervention in the local environment. Should an environmental scientist dismiss spirituality as superstition if his field of study requires him to do so, or not? The Arctic Council's Guidelines for Environmental Impact Assessment (EIA) in the Arctic specifically point out the need to take the perspectives and requirements of indigenous peoples into account (Arctic Environment Protection Strategy 1997).

In conclusion, human classifications of the Arctic environment could range widely. Traditional perspectives and observations may apparently range from very esoteric to quite easy to apprehend from a scientist's perspective. More practical to LCA researchers looking into the Arctic are extensive scientific reports such as AMAP (1998) and its successors, which at times are tidily structured into impact categories and damage categories that resemble those of LCIA. The choice of relying on typical scientific or expert judgment in a PhD project is not controversial, but other potential solutions do exist.

Importantly, the Arctic is not only perspectives, but an actual, living environment which does not necessarily behave within the limits predicted by our systems of categorisation. The risks involved when humans intervene can be illustrated by an example. In the 2011 workshop connected to this project, one participant meticulously presented the case of the 1980 Almö bridge collapse. "Every single" safety precaution that had been conceived had painstakingly been implemented, but it had simply not been imagined that a large ship could ever come slightly off course and thus collide with the arc bridge. The bridge collapsed, and this collapse in turn caused seven cars to end up in the freezing waters below, with fatal consequences. The participant concluded that it is imperative to have a good imagination when we deal with real-life situations. This advice seems to imply that some measure of quality is required in the empirical material, whether on the Arctic or a particular case. Optimally, in the treatment of important questions, ordinary, every-day judgment needs to be transcended. Or, as Steen (2006) points out, at least within the social sciences it is more often than not commendable, not questionable, to transcend peoples' everyday perspective through criticism.[7] Of course, though, exactly how held perceptions can be transcended to a higher level of quality in a consistent and at the same time acceptable manner is not obvious.

In summary, much of the fundamental problem of weighting involves not only how humans act to conceive environmental objects, which is challenging enough to investigate, but also how they *should* conceive the environment. The complexity extends to the validation of whether correct choices have been made over the course of the research process of the project. Whereas this thesis constructs a certain overall argument and is bound by convention to do so with a certain conviction, the question of whether or not something vital is eventually forgotten or left out is challenging to answer with certainty.

### 1.2.3. RESEARCH QUESTIONS

In the above, much has been written about the complexities and the comprehensive scope involved in the project. These are key features of weighting and the project, and the research had to be designed accordingly. As also pointed out in the beginning of chapter 1, the research approach involves to explore the concept of weighting from a holistic perspective, and at some point to make the sensible choices required in order to finally narrow, conclude and close this exploration, yielding the required output.

In brief, these are the research questions of the project:

1. In general terms, which categories of facts are of higher rather than lower importance to LCA weighting?
2. What is a high-quality weighting method according to LCA experts?
3. What are the numerical priorities between different environmental impacts in the Arctic environment?
4. In view of sustainability concerns, can an "optimal" weighting methodology be identified?
5. What is the set of weighting factors that can be derived from this weighting methodology?

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[7] Wittgenstein's *Tractatus* puts a perhaps similar point like this: "*In order to tell whether a picture is true or false we must compare it with reality. It is impossible to tell from the picture alone whether it is true or false. There are no pictures that are true a priori. (...) A logical picture of facts is a thought. (...) If a thought were correct a priori, it would be a thought whose possibility ensured its truth.*" (ch. 2-3)

6. What are the implications for the environmental performance of CCS technology?

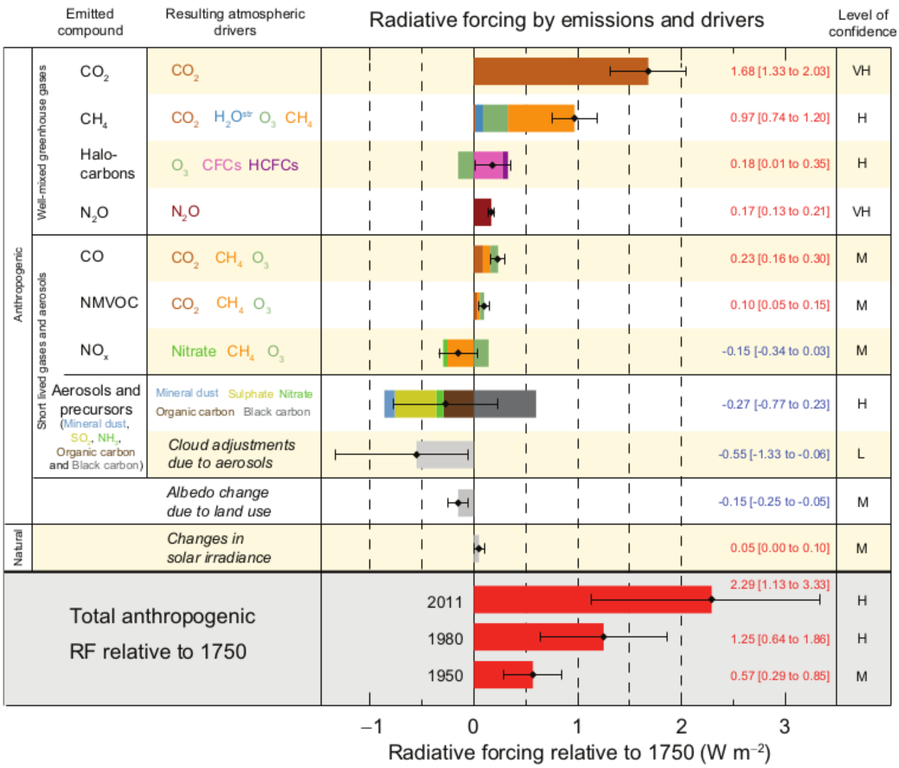
Eventually, these research questions correspond loosely to the roman numerals of the supporting papers provided in the appendices: Question 1 is answerd by Paper I, Question 2 by Paper II, etc. However, Question 6, which pertains to the CCS case, is answered in this document.

Answers to the research questions are outlined in the Conclusion chapter of this document, chapter 5.

The case of CCS is treated in this document, and the next section will provide a brief introduction to this technology.

## 1.3. THE CASE: CARBON CAPTURE AND STORAGE (CCS)

Greenhouse gas emissions to air cause greenhouse effect and global warming. $CO_2$ is one of several drivers for global warming, as illustrated by figure 4 (IPCC 2013, p. 12).




# Figure 4. Radiative forcing estimates in 2011 compared to 1750 (diagram from IPCC 2013, p. 12)

According to IPCC (2013, p. 25),

> *Cumulative emissions of $CO_2$ largely determine global mean surface warming by the late 21st century and beyond (...) Most aspects of climate change will persist for many centuries even if emissions of $CO_2$ are stopped. This represents a substantial multi-century climate change commitment created by past, present and future emissions of $CO_2$.*

These cumulative emissions are important because emissions accumulate in the atmosphere. The $CO_2$ concentration increase according to IPCC (2013, p. 10) is shown in figure 5.

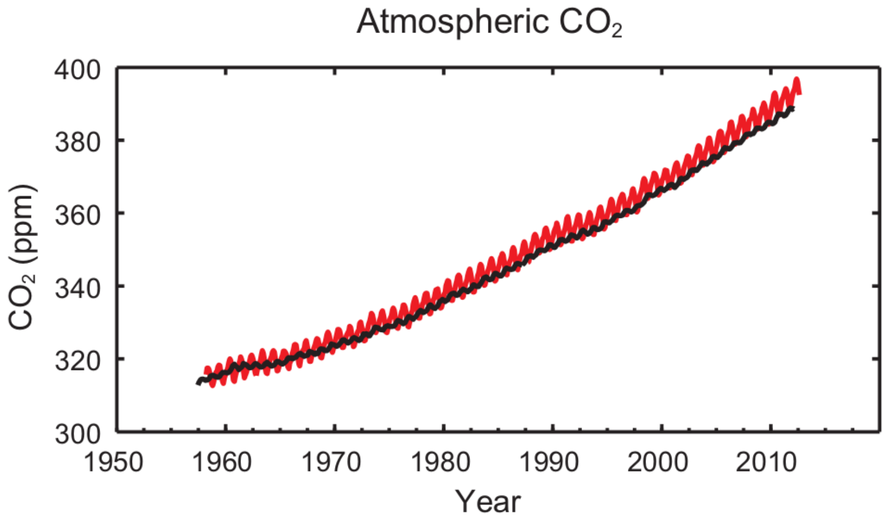



**Figure 5. The atmospheric CO2 concentration increase over the last decades has increased radically (from IPCC 2013, p. 10)**

$CO_2$ emissions to air also eventually accumulate in seawater due to further uptake of carbon by the ocean, and leads to marine acidification (IPCC 2013, p. 24). This is another critical and global environmental threat (Orr et al. 2005; Makarow et al. 2009). Marine acidification is expected to be more substantial in cold waters, such as in the Arctic (Loeng 2008, p. 18). The latter report states (my translation into English, my emphasis):

> *[i]n the Barents Sea the* ***pH*** *is expected to have* ***dropped by 0.5*** *units in 100 years. [...] By the end of this century, the amount of* ***hydrogen ions*** *in the ocean* ***will have tripled*** *in relation to 150 years ago.*

As also illustrated by the findings of Thomas et al. and IPCC in section 1.1.2, the trend in figure 5 cannot continue. In moral terms, we are unable to emit $CO_2$ to the atmosphere or the ocean, but at the same time $CO_2$ gas is the main waste from fossil fuel combustion, which has gained widespread and increased, if not popularity, then at least extent over the last few centuries. As fossil fuels cause affluence and affluence causes influence and power, fossil fuel combustion is not decreasing despite warnings from scientists. Hence, a *combination* of global warming mitigation and continued fossil fuel combustion is regarded as a pragmatic option.

In section 1.1.2, it was pointed out that Thomas et al. (2004) recommend "carbon sequestration" as a tool for mitigating global warming. This refers to the technology of *carbon capture and storage (CCS)*. This technology separates $CO_2$ from the flue gas of a large point source (typically, a power plant or a major industrial site), and stores this $CO_2$ underground. In this way, it would seem that by now old-fashioned fossil-driven power plants can be turned into modern, environmentally friendly "zero-emission" plants merely by installing a few extra modules: A capture plant, some form of transportation facility between the plant and the storage site (typically dominated by pipelines), and a suitable underground storage facility. An abundance of research has been, and is currently, conducted on the technical as well as societal details of CCS. Several scientific journals are partly or fully dedicated to CCS, one example is the *International Journal of Greenhouse Gas Control*. The biennial international conference series GHGT is a key meeting place for CCS researchers. Several reviews of the state of the art of CCS are available. A report by the IPCC (2005) provides a comprehensive, albeit by now slightly dated overview of CCS.

The basic idea behind CCS can be illustrated in several ways. One simplification is to consider both fossil fuels and $CO_2$ as carbon, C. Carbon can be found in five main reservoirs, see figure 7; note that carbon moves around in this system as described by the "carbon cycle". For the case of a natural gas-fired power plant, carbon will be transferred from the Earth's interior (natural gas) to the atmosphere ($CO_2$), with accumulation in the atmosphere and depletion in the crust as a result. With CCS, carbon emissions to air can instead be directed back to the underground, to more or less the same reservoir that the carbon originated from. Hence, no accumulation takes place in the atmosphere (or subsequently in the ocean). Of course, this simplified outline assumes that stored $CO_2$ and natural gas behave similarly in the underground, and that there thus will be little or no $CO_2$ leakage.

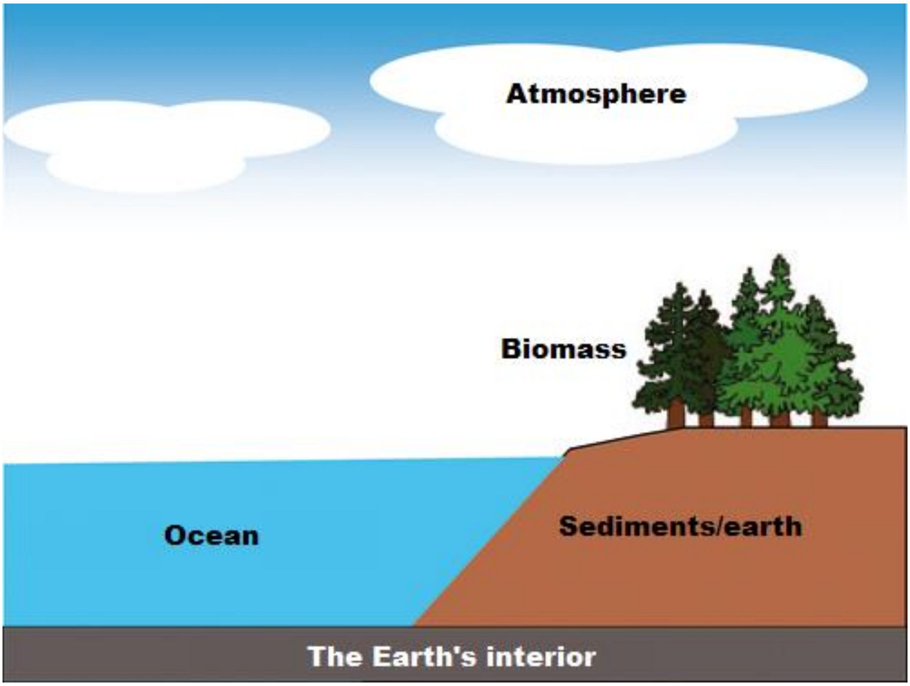



**Figure 6. Carbon is a constituent of the atmosphere, of biomass, of sediments/earth, of the oceans, and of the Earth's crust and mantle. (Diagram adapted from Det kongelige landbruks- og matdepartement 2009, p. 41)**

Several CCS capture technologies are under constant development. According to Modahl et al. (2012), the "technology of choice" for current coal-fired and gas-fired power plants is so-called post-combustion $CO_2$ capture, in which amines are used as solvent – one typical amine of choice is MEA, or monoethanolamine. Other capture approaches include "pre-combustion" and "oxy-fuel" technologies.

As for CCS storage, a multitude of topics are currently under scrutiny, often with the objective of identifying storage sites that have optimal geological conditions in general, and which control and reduce migration of the $CO_2$ and storage leaks in particular. For instance, one possibility which is currently analysed as a solution to any leakage problem is storage through mineral carbonation (Ragnheidardottir et al. 2011). It can also be noted that on-shore and off-shore storage raise somewhat different challenges.

CCS is not really a new technology. Equipment involved in each of the respective steps $CO_2$ capture, $CO_2$ transport and $CO_2$ storage was already known, tested and in use before CCS for global warming mitigation purposes was conceived, although it had not necessarily been tested at the massive scale required in order to make a difference to the climate change equation. For instance, Statoil started injecting $CO_2$ into the Sleipner field in the 1990s – for the purpose of enhanced oil recovery (EOR), not global warming mitigation (Hawkins et al. 2009).

Notwithstanding all the technical details, does power generation with CCS in practice mean "zero-emission" power? No, only provided a very simplified model where $CO_2$ is seen as the only emission and cause of environmental impact, where no $CO_2$ emissions are caused by the CCS facility, where there are no life cycle impacts from e.g. value chains and waste, and where there is perfect storage of all $CO_2$ with no subsequent leakage. Of course, these could very well become valid *approximations* in the far future, but until then the life cycle assessment studies can be used calculate life cycle emissions of the technologies in question. LCA studies of CCS demonstrate that the technology has several environmental side effects. For a general overview and review of such LCAs, see the report of IEAGHG (2010) and two corresponding articles, Marx et al. (2011) and Zapp et al. (2012), as well as Strazza et al. (2013) and Corsten et al. 2013. In general, conclusions are:

- CCS reduces $CO_2$ emissions to air, although in a life cycle perspective these emissions are not eliminated
- The climate change impact is thus reduced
- All other LCA environmental impact categories are worse off with CCS

Whereas these reviews provide plentiful analysis and background information, they do not extensively cover weighting in LCA of CCS, which is the prime focus of this thesis. This ground is to some extent covered by Modahl et al. (2012), where three existing weighting methods are used. The conclusions are mixed. For scenarios with gas boiler and process integration, respectively, the total environmental impact is according to weighted results lessened. If a biofuel boiler is used, 3 out of 6 results indicate a worsened total impact. The main reasons for this poor result are worsened depletion of reserves and (human) life expectancy according to the EPS2000 weighting method, and worsened (human) respiratory inorganics and terrestrial ecotoxicity according to the IMPACT 2002+ weighting method.

As a whole, according to the weighted scores of Modahl et al. (2012), ecosystem damage from climate change does not dwarf other impacts, as one would perhaps expect from the critical observations of Thomas et al. (2004) presented in section 1.1 and the large amounts of $CO_2$ sequestered. In general, this makes conclusions on the total environmental advantage of implementing CCS somewhat limited and unclear. The indistinct conclusions are potentially fatal to the technology, as CCS is an expensive surplus cost to power generation with no other function than its environmental purpose (although carbon sequestration can be used to enhance oil recovery). An important question is whether the findings of Modahl et al. are due to the CCS concept being fundamentally flawed, or whether it reflects weighting methods that fail to accurately take into account the deterioration of the sustained environment (or, the deficiency of sustainability) caused by climate change impacts.

The fact that LCA studies of CCS demonstrate that CCS has environmental side effects is in itself an unsurprising conclusion, or not really a conclusion at all, because it is part of the scope of LCAs to document, precisely, environmental side effects. Once the choice to perform an LCA has been performed, the question is whether the side effects investigated are significant, not whether they exist or not. (Again, note that typical environmental side effects, or environmental impacts and damages that are documented by LCA studies, are shown in figure 1 above, in section 1.1.3).

Why are these impacts and damages necessary or even interesting to investigate? As mentioned, it would appear obvious that CCS in itself is a good idea merely from the massive ecosystem impact of $CO_2$ emissions outlined in section 1.1.2. Nevertheless, CCS has proven to be controversial. In the Netherlands, a large on-shore $CO_2$ storage facility at Barendrecht was halted. This case has been thoroughly documented by Feenstra et al. (2010) and Kuijper (2011). The latter paper indicates reasons such as public fears over $CO_2$ leaks and that the facility would not be able to generate many local jobs. For on-shore $CO_2$ storage in general, public fears over gas leakage have proven a recurring impediment. For the Norwegian case of full-scale CCS (capture, transport and storage) at Mongstad, leakage from the storage site was never a large public concern, probably because the storage facility was intended to be off-shore. Instead, local toxicity concerns from the capture process and costs (as well as Norway’s 2013 election) delayed and eventually halted the project.

Once we accept the use of LCA or similar broader outlooks on the effects of CCS, it becomes obvious that CCS cannot be regarded as an enabler of, as it were, magic *ex nihilo* and “zero-emission” energy production. The question, then, remains as to how power production with CCS fares environmentally, at least compared to alternatives based on renewable energy, and whether construction of a CCS facility in the Arctic region makes any difference.

# CHAPTER 2. THEORETICAL BASIS: THEORIES USED, RELATION TO THE PHILOSOPHY OF SCIENCE, AND THE COHERENCE OF THE SUPPORTING PAPERS AND THE PHD PROJECT IN GENERAL

Overall, the approach of this project has been cross-disciplinary, and can be regarded as a hybrid between an open-ended and to some extent normative inquiry and what Kuhn (1962) calls paradigmatic "normal science". Over the course of the project, this self-contradiction has been a constant headache which has been difficult to describe justify. Only *post hoc* was it recognised that the "post-normal science" described by Funtowicz and Ravetz (1994) to some extent can describe the process and its difficulties.

In post-normal science, the concept of "quality" is used as an ordering principle within a seemingly chaotic maze of information overload. Where Funtowicz and Ravetz emphasise the social dimension as important, however, the scientific ideal in this project has to some extent tilted towards normal natural empirical science, and the highest-quality objects of this empiricism was often assumed to be something along the lines of the "quantifiable core essence of large-scale systems". Of course, humans and human knowledge on a particular topic can be described as such systems in their own right.

The sometimes self-contradictory nature of cross-disciplinary research can be described in many different ways: Normal science's rigid perfectionism can be pursued, but never really satisfactorily fulfilled in the context of trans-paradigmatic, post-normal "science". For instance, whereas normal science can be regulated by a "scientific method", and criteria such as "falsifiability" and "reproducibility", normative ethics is a more divisive topic: there is less universal agreement on what is "good" and what is "bad".

Another contradiction is that a complete understanding of the essence of environmental damage, which may be needed to fully understand the field weighting/valuation, will in some way or another relate to the noun *being*. However, this term is difficult or impossible to define, and thus cannot seamlessly be used in logical reasoning: it is or refers to a oneness, or a *genera generalissima*. Thus, in brief, as a substitute for logical reasoning involving such terms, some undefined notion of good or acceptable judgment must be involved at all stages in order to create and implement the eventual logical structure 1-4. One solution to this dilemma is an appeal to authority in Papers II and III.

The final logical structure of the project is relatively simple, and can be summarised thus:

1. Suggest a "high abstraction level" as an ordering and unifying principle in the "post-normal-like" information overload situation experienced in the project (Paper I)
2. Experts emphasise different criteria for weighting methods (Paper II)
3. Their suggested irreversibility criterion is chosen in this project (Paper IV)
4. From this criterion, these are the weighting factors (Paper V)
5. Experts have suggested Arctic scaling factors for regionalisation of weighting factors (Paper III)

In summary, the outcome of the project has had a structure (1-5 above, and also outlined in Paper I), but this structure is in turn inevitably interweaved with a less explicit normative and philosophical inquiry. The following subchapters will review a selection of adjacent terms and methodological observations that serve to further illuminate these links. Each subchapter will discuss a selected issue, and will on the basis of these issues propose different perspectives on the interconnections between the adjoining papers.

Sections 2.1 – 2.7 are thus intended to put the individual papers into a larger context. The individual papers are presented and briefly contrasted in chapter 3.

## 2.1. METHOD / NARRATIVE STRUCTURE

### 2.1.1. WHAT IS THE GENRE OF THE NARRATIVE?

The knowledge assembled during the project could possibly have been related by means of other types of narratives or genres. This would in turn have influenced the results.

The research questions ask for a development, an establishment, of weighting factors. If the aim of the project instead were to investigate how the phenomenon of weighting matches an (informally speaking) post-modern worldview, other aspects would have been emphasised. A less ambitious approach than the one chosen in the project would have been to show how weighting is arbitrary, subjective, how different methodologies give different results, etc. The conclusion would easily become that there are no superior ideas or grand narratives for weighting, meaning that it is arbitrary, subjective and contextual, and that nothing in general can be concluded about the issue (cf. Lyotard 1979; Finnveden 1997). The main problem with this narrative is that it can promote a logic that becomes intellectually somewhat lazy, where any weighting approach is good enough no matter how little effort was put into it. Is it perhaps a tad too easy for a researcher to make surveys and measure people's held opinions? In a certain way, Supporting paper III on the Arctic environment used such a methodology, and it was assembled quickly, painlessly and with not much reflection required compared to the rest of the papers.

This phenomenon, that an approach is "practical for scientists" was identified as a criterion for good weighting methods in the review of Paper II. However, the paper also warned against this criterion, as more practical methods may sometimes be too simple. In particular, Funtowicz and Ravetz (1994) point out the risk of "hyperprecision" when people are asked to give estimates or even "guesstimates": The numerical results in post-normal science will easily be deceptively precise, and their uncertainty will be difficult to assess because most of the uncertainty is embedded in qualitative issues such as the choice of methodology itself.

### 2.1.2. THE NARRATIVE OF AND THEORIES USED IN THE PHD PROJECT

The research questions, and the content of the Papers (see Appendices), was developed according to the requirements of the subject-matter, not necessarily in accordance with the wish to obtain an eventual orderly and one-dimensional narrative structure. Nevertheless, it is possible to structure the steps taken during the project in a more or less chronological, one-dimensional list (the arrow --> does not mean "implies", but signifies development):

1. Start of project: Weighting is arbitrary/in everything
2. → Weighting is subjective, and thus arbitrary (**Finnveden 1997**)
3. → Subjective is not arbitrary, so weighting is not arbitrary (**Klöpffer 1998**)
4. → Problem: Subjective depends on context (priming, framing) (**Goedkoop 2013-2**)
5. → Context is not arbitrary, so subjective judgement is not arbitrary (**Construal level theory**)
6. → Context can be controlled (priming, framing); use of current knowledge for Arctic case (**Paper III**)
7. → Criteria for controlling context of subjective weighting judgment (**Paper I**)
8. → Controversy: the context should not be controlled, as this denies respondents free will (**Review of Paper I**) However, it is opaque how weighting factors are conceived and unclear to which extent they can be trusted (**Steen 2006**)

9. → Observation: Need for more firm ground (but how?)
10. → "Objective" weighting principles would be desirable, but none seem to exist (**Soares et al. 2006; Ahlroth et al. 2011**)
11. → "Cognitive phase change": Intersubjective/quasi-objective, albeit reductionist, principles for weighting take shape or "crystallise" – weighting/valuation can be based on axioms, or principles (**Paper II**)
12. → Definition, sorting and eventual choice of reductionist externally imposed or "quasi-objective" principles (**Paper IV**); methodological justification found in peace research (**Galtung 1996**), grid-group typology (**Douglas 1972**), planetary boundaries (**Rockström et al. 2009**) and limits to growth (**Meadows et al. 2004**)
13. → Deduction of reductionist weighting factors from identified principles (**Paper V**)
14. → Words of caution on the limitations of reductionist weighting factors (**Paper IV, Paper V, this document**)
15. → Formulation of background (**first submission of Paper I, plus Paper IV, Paper V, this document**)

A simplified version of this process was later made into a key point in the final version of Supporting paper I (ref. that article's figure 1). The earlier drafts of this article focused more on construal level theory and how it could be employed e.g. in questionnaire design, but did not consider how to proceed after increasing the level of generalisation. If a good, but very generic idea cannot be implemented or communicated in practice, it is perhaps not a good idea anyway; the article also discusses this problem.

The chronology above is simplified: informal inquiry into an "objective" or "quasi-objective" form of weighting started in the beginning of the project, but was further intensified after the first review of Paper I (step 8) and a PhD conference at Aalborg University (in 2012). Also, the overarching ethics, philosophy and philosophy of science at each step has of course been a constant source of either understanding or puzzlement. As also suggested above, the term "objective" in this context is intended to mean something like "does not have an individual human subject as an object", but not "uncontroversial". This was made into an important point in Paper IV, but in its abridged and resubmitted version the use of the term "objective" was toned down, exactly because it is ambiguous and its use thus can come across as arrogant and become a source of contention.

The "cognitive phase change" in which one moves from a perhaps elusive fog of holistic, but imperfect understanding of the problem to reductionist, but tangible principles or categories is important. The prior "holistic" understanding may perhaps be criticised as redundant, but it appears to the author to be part of the process, as it prevents error and allows an understanding of the reductionism or "error of analysis" involved. Circumspecting or investigating the problem complex from several angles, i.e. by reading related literature that may or may not come in handy, may thus be a requirement in the early phases. It can be contended that the fog of ideas at the stage of "holistic", uncategorised understanding of the problem is a more primordial form of understanding than the eventual terminological, principle-based understanding. This is, however, a fundamental philosophical question which cannot be definitively clarified here.

### 2.1.3. EMPIRICAL DATA USED

The empirical data used in the PhD project is as follows:

- Paper II: Articles and reports that suggest "criteria" for good LCA weighting
- Paper III: A survey submitted to Arctic environmental scientists
- Paper V: Data on speciation rate, human birth rate and economic growth; estimates from literature
- This document (below, see ch. 3): LCA/LCI results from Modahl et al. (2012)

## 2.2. RELATION BETWEEN WEIGHTING ON ONE SIDE AND ETHICAL THEORY, SCIENCE AND "IRRATIONALITY" ON THE OTHER

The arithmetic construction of decision support by means of weighted LCA results resembles utilitarianism. Utilitarianism suggests that alternatives should be assessed and compared by summing positives and negatives. The option which in sum causes greater "happiness" (Bentham 1780/1823, page 1) or "utility" (Mill 1863/1879, chapter 2) is thus the best option. This general idea is referred to as the "greatest happiness principle" (Riley 2013). If a utilitarian analysis is performed by means of arithmetics, it is similar to the approach of a weighted *pro aut contra* inquiry (Krabbe 2010). Superficially, utilitarianism looks like a rational and logical approach towards ethics, which is relatively similar to the consequentialist approach to (potential) environmental intervention found in LCA and LCA weighting. An immediately emerging difficulty, however, is how to define happiness or utility. This hindrance is mirrored in LCA's weighting question, which can be understood to ask how to define sustainability, or alternatively the relative "severity" of unit environmental impacts/damages. As LCA measures negatives, not positives, happiness or utility in the LCA context needs to be redefined as some form of avoidance of greater environmental harm.

Whereas somewhat rational procedures can be proposed for the ultimate structure of utilitarianism (*e.g.* Johnsen 2002), happiness and unhappiness do not seem to be immediately measurable. If seen as more comprehensive than mere immediate pleasure or pain, the concept at least to an extent defies definition, and particularly when non-human subjects are involved: it becomes a very complex or even holistic concept. Hence, the apparently rational, logical and scientific-like nature of utilitarianism (and, by analogy, LCA) is undermined when this higher vantage point is assumed. An inquiry into the nature of happiness/utility and LCA weighting, respectively, in part approaches something irrational and illogical, or at least something which is not easily available through empirical studies. This poses certain limitations for the discourse on weighting. The irrational, illogical and unscientific part of weighting cannot *easily* be discussed in a rational, logical, scientific journal-like and coherent manner.

To an extent, most research deals with irrational or value-based elements. The role of irrationality in research has been investigated by several authors. Cortner (2000) shows how values enter any scientific inquiry, through several pathways. Bauer (1992) explores and criticises the notion of a scientific method. He proposes, for instance, that every scientific inquiry can be understood to start out with chaotic, unreliable and subjective “nonsense”, which step by step is purified through a knowledge filter (ibid. p. 45). For instance, hypothesis generation is a process of invention, and how invention should optimally take place is not really concisely and universally understood: it is, perhaps, an unstructured process which involves trial-and-error, guesswork, subjectivity, *etc.*, but it is nevertheless an important part of what researchers do.

As the field of weighting as a whole is not based on one robust scientific framework, hypothesis generation becomes a large part of any thorough inquiry into weighting, certainly larger than what is the norm in scientific inquiry. Current weighting sets may arguably be called more or less unproven hypotheses for how weighting should be carried out. Nevertheless, as weighting factors are based on data collection and some form of methodology, weighting also has traits that are similar to science. Hence, weighting can at least to some extent be regarded as a scientific inquiry in which hypothesis generation and invention (creativity) are more prevalent and require more focus than what is the norm.

In conclusion, we can - preliminarily - observe that no *fully* rational, logical or “scientific” recipe for how to perform weighting seemingly can be devised. How do we deal with the subjective or irrational part of the equation? Some of the more philosophical questions that may arise are:

A. How to define the difference and relation between subjectivity and objectivity in weighting/valuation
B. How to define “good” judgment in relation to weighting
C. How to define the merits and limits of free will and “improvised estimates” in weighting tasks

D. How to understand causality in weighting: were the final weighting factors ultimately caused by something we can identify?

It follows that the research questions that were presented in section 1.2.3 were not the only fundamental questions that had to be dealt with in this project. Question A is treated in Paper IV; Question B is dealt with in all papers, but particularly in papers I, II and IV; Question C is dealt with in all papers, but particularly in Papers I, IV and V; Question D is briefly discussed in Paper V (in how damage and generation can have different kinds of causes).

LCA weighting is (or was chosen to be) regarded as a comprehensive topic, and this caused a relatively philosophical approach to this project, as theories normally need to be more wide-ranging than the topic they aim to explain. Over the course of the project, at least three overarching theories were employed: Construal level theory (Paper I; although its importance in the paper was toned down in its latest version), and grid-group typology and peace research (Paper IV). Moreover, tacit ideas from system dynamics are likely to have influenced Papers IV and V. Once the theoretical basis had painstakingly been devised, the identification of the actual data for weighting factors (Papers III and V) proved to be relatively straightforward in comparison.

## 2.3. THE DEMARCATION PROBLEM: IS WEIGHTING SCIENCE?

It was pointed out above that ISO 14044 does not consider LCA weighting to be science. This statement, and its implications, can be questioned. Where should we draw the dividing line between science and non-science, and is everything which is not science nonsense? These are questions that pertain to the *demarcation problem* in the philosophy of science (see *e.g.* Laudan 1983).

The demarcation problem is highlighted by the following claim about LCA weighting in the ISO 14044 standard (section 4.4.3.4.2):

> “Weighting steps are based on value choices and are not scientifically based.”

This would seem to suggest outright that weighting is outside the demarcation line of science, and that it – one would assume – cannot be treated in a scientific context. However, science is sometimes divided into “hard” and “soft” sciences. The ISO standard could be interpreted to refer to hard science. In this case, it will agree that weighting can be dealt with within the sphere of soft science. Or, it might claim that weighting even cannot be investigated by any kind of softer science. However, this would seem to be unreasonably rigid. It would also impose unacceptable constraints upon researchers, as it would render the weighting concept essentially impossible to use.

There is a particular reason why "hard" natural science is not applicable as a framework for weighting. Such research has a worldview which is centred on modern physics. Modern physics is in turn fundamentally based on the Cartesian and Newtonian understanding of the world, in which all matter is *de facto* regarded as inanimate, or dead. Weighting has to take into account the value of different subjects exposed to harm, and as the value of an "object" tends to increase with the presence of "life" in it, the mentioned worldviews cannot form a complete theory of weighting.

As most science, whether hard or soft, is based on several of the tenets of Descartes and Newton, one may wonder whether this actually disqualifies weighting from the scientific field altogether. Indeed, certain what we would call pre-scientific notions may illuminate a few ideas fundamental to weighting. For instance, the weighting principle eventually developed in Papers IV-V (see below) turns out to quite accurately reflect an axiom by medieval philosopher-theologian and scientist Albertus Magnus:

> The nobler something is, the more slowly does it acquire its perfection
>
> (Albertus Magnus 1263/2008, Book 9, Question 3, p. 304)

This quote is a small hint that natural scientists during the scientific revolution lost track of some quality concepts, such as "nobility" (cf. the "regeneration time" of LCA's "safeguard subjects").

In several of the supporting articles, the term "post-normal science" (Funtowicz and Ravetz 1994) is referred to as relevant to the demarcation problem. The demarcation problem also turned out to be related to the definition of weighting and normalisation, and there is some current discussion on where the line between weighting and normalisation should be drawn (Bjørn and Hauschild 2015; Pizzol et al. 2016). This is also discussed in some of the articles and elsewhere in this document.

## 2.4. REFLECTIONS ON THE PROBLEM OF REGRESS

The regress argument in the philosophy of science is that any proposition requires a justification, and that every justification requires another justification, which in turn requires yet another justification, *et cetera* in an infinite regress. This would imply that in seeking the final answer to a problem the best approach is to ask the question "why" indefinitely. It shows how demanding perfect justification when inquiring into real-life questions ultimately leads to absurdity and infinity. In practice, though, why is not always the fitting or sensible question to ask. This correspondingly means that a demand for perfect justification refers to a perhaps praiseworthy ideal, which is not sensible in practice. Nevertheless, critical ethical and philosophical analysis requires premises to be questioned and why questions to be asked. This particularly applies when answers we obtain do not seem to be good enough.

The idea of a chain of why questions indeed forms some of the informal philosophical background of Paper I, which is linked to construal or abstraction levels. The review in Paper II to some extent retraced certain of the early ideas about weighting of LCA researchers, but it does not further question *why* they in turn came up with their suggestions. The introductory justification of "quasi-objective" weighting in Paper IV required the application of not only one, but two virtual "theories of everything", grid-group typology and peace research. These were not further questioned with the question of *why* except informally: they *seem* to be robust, and can serve as, if not perfect, then at least pragmatic foundations.

The idea that every idea in this PhD project can be perfectly explained and justified is thus somewhat presumptuous. Ultimately, the final litmus test of success in the more philosophically directed Papers I and IV has perhaps simply turned out to be the successful construction of sufficiently convincing text, provided an imagined well-informed and critical, although not absurdly perfectionistic, audience.

The Problem of regress indicates that there are some higher-level "why" questions which are difficult to grasp, and difficult to answer. These questions tend towards philosophy: they are perhaps important, but also immaterial, high-flying and arguably "pompous". Timaeus in Socrates in Plato's dialogue *Timaeus* seems to recommend dealing with or aiming for these lofty spheres primarily in the beginning of an enterprise (Plato 360 BC/2008, section 1). The process described in Paper I can be interpreted to agree with this view.

## 2.5. RELATION BETWEEN SCIENCE AND PHILOSOPHY FROM THE VANTAGE POINT OF METAPHYSICS

In mediating between academic disciplines such as ethics/philosophy and natural science, metaphysical concepts may be useful. An application of metaphysics is perhaps a sign of an overly meticulous or careful inquiry. Nonetheless, typical LCIA damage categories indicate that careless weighting could lead to adverse consequences. Let us therefore briefly note a few relevant overarching issues.

As mentioned in the above, completeness or holism is an important criterion for weighting methods; this is also established by Johnsen and Løkke (2013) [Paper II]. According to Bertalanffy (1972), general systems theory, which LCA has connections to, is partly based on Aristotelian notions of holism. Aristotelian physics is a kind of pre-Illumination rejection of atomism, in which the sum is regarded as greater than its parts. In this paradigm, holism may be approached through Aristotelian *forms* (Hill 2007), but to scientists these are in practice mysterious entities. It is not clear from a metaphysical position what are the forms, or formalities, framing or priming, required for proper weighting, and how they can be elicited.

This mirrors a noteworthy divide within academia as a whole. Relevant philosophical and ethical questions include morality vs. moral relativity; deontological ethics vs. teleological ethics vs. virtue ethics; the question of free will; the nature of the is-ought-divide, and, perhaps importantly, the problem of universals (cf. e.g. Russell 1946). Other relevant questions are the positivist dispute, the definition and nature of life and intelligence, the relation between the *vita activa* and the *vita contemplativa* (Arendt 1958/1998; Aquinas 1274/1948, II-II, Q. 182), the definition and role of causality (Beebee et al. 2009; Falcon 2012) – and more. If the more concrete value issues of weighting considered by Finnveden (1997) are added to this, an identification of weighting factors or arguments in favour of a particular manner of weighting with *universal superiority or acceptance* seems to be remote – at least in theory.

The notion that weighting is entirely subjective allows a praiseworthy amount of freedom and plurality of opinion, but unfortunately it is also at the root of the metaphysical degrees of freedom that made the previous paragraph difficult to read. At the cost of reduced plurality, an "anything goes" approach to weighting can be replaced or at worst complemented by deriving weighting sets from principles anchored in *common understanding*, or what Bourdieu calls *doxa*, what Kant calls what is *a priori* given, (perhaps) what Aquinas (1274/1948, I, Q. 85 and II-II, Q. 8), calls *understanding*, what Gadamer calls the *intersubjective*, and what Euclid calls *axioms*. To some extent, the methodology cannot be entirely based on scepticism, and the existence of some form of common sense must be assumed.. Perhaps this reflects a duality attributed to Kong Fuzi by Döblin (1949): it is beneficial to understand a universal system which exists outside human will (in our case related to environmental concern), but it can only be actualised through human cooperation. Some traits of this universal system have been identified in the Papers for the case of LCA weighting.

Considering the supporting articles, examples of "universal systems" that have been investigated are:

- Abstraction levels (Paper I)[8]
- Criteria for evaluation of weighting methods (Paper II)
- Subjective inquiry and spatial diversity (Paper III)
- Peace research[9] (Paper IV)
- Grid-group typology[10] (Paper IV)

[8] A theory from social psychology. See for instance Trope and Lieberman (2010)

[9] This field of study was coined by Johan Galtung. See e.g. Galtung (1996)

[10] A theory from social anthropology, introduced by Douglas (1973/1996)

- Reversibility and regeneration time as an indicator[11] (Paper IV)
- Non-atomic causality[12] (originally in Paper V, removed in last version)

## 2.6. WEIGHTING AS MODELLING: RELATION TO SYSTEM DYNAMICS

One vantage point to weighting is to regard it as a form of modelling. Papers I and III can be understood to regard weighting as a form of modelling of an imagined “sphere of opinions” on weighting. This stability of this sphere of opinions was eventually questioned in Paper IV, and consequently it was also questioned whether it eventually was the correct object of analysis. Papers IV and V can be claimed to move into the field of system dynamics, as they investigate key indicators of “objective” complex systems - objective as opposed to subjective (although inquiry into the subjective can be seen as analysing “the complex system of human reasoning”), but certainly not objective as in a guarantee of robust results).

Homer (1996) describes how system dynamics relates to the philosophy of science. He outlines how feedback loops can be modelled through trial and error, and next be validated. The system characterised in Paper V is, however, very large and stupefyingly complex at a more detailed level. A threat involved is that of reductionism, *i.e.* that the complex system identified is too narrowly conceived and thus insignificant in relation to the full scope of weighting. Reductionism is, in turn, not straightforward to analyse, as its detection requires “thinking outside the box”. A related risk is to, for instance, assume linear relations in what eventually turns out to be non-linear systems. For instance, the idea of regeneration time does not take into account non-linear “tipping points”.

[11] This idea reflects a literal interpretation of the “sustainability” term

[12] This refers to the idea that it is the system as a whole (e.g. the whole Earth-system “Gaia”), not merely one of the necessary isolated processes alone (e.g. genetic mutation) that causes certain pinnacles of the whole system, e.g. the successful evolution of a persistent species. The consequence is that the sluggishness in the development of these pinnacles is relatively stable, because the slowness involved cannot be removed or eliminated through “quick fixes” of isolated elements or processes. This view of causality has, arguably, more in common with the teleological causality of Aristotle than with the Newtonian view of cause and effect. The former is, however, not consistent with the mind-matter duality of Descartes. The notion that many different forces in practice converge to form a key “noble” outcome probably requires a certain acceptance of hierarchies, such as the idea that some objects are more noble that others, actually or potentially. Cf. the Albertus Magnus quote in the above.

## 2.7. IDENTIFYING "THE GOOD" THROUGH COMPLEMENTARITY: A TOP-DOWN METHODOLOGICAL APPROACH THAT AIMS TO DESCRIBE THE TOTAL ENVIRONMENT MATCHES A BOTTOM-UP SOCIETY

The non-anthropocentric weighting method described in Papers IV and V recalls the term coined by Nagel (1986), "the view from nowhere". There is also a parallel in the "veil of ignorance" of Rawls (1971). However, humans are inclined to care first and foremost for humans, animals and concerns that are more proximal to them. As is particularly obvious for the case of raising small children, caring for one's immediate surroundings can also be a moral imperative, and some will say more so than being preoccupied with semi-hypothetical wholes such as the total environment.

Now, it is possible that both "the view from nowhere" and a focus on what is proximal can be overestimated and exaggerated. If a "quasi-objective" arithmetic weighting method based on observations of the limitations of the system we live within is *yin*, a subjective take on the world is *yang*. Arguably, both must be present. However, it is perhaps more appropriate that the latter is devoid of explicit arithmetic calculation than that the former.

As pointed out in Papers IV and V, "impersonal" weighting would be more appropriate in cases where there are already sufficient safeguards in place for maintaining both "invididualist" and "egalitarianist" cultures, *i.e.* in absence of top-down totalitarianism. Or, to reverse the perspective, it might be more fitting in cultures where how to retain and sustain the whole has become both secondary and tertiary to overindulgence, with some form of genuine equilibrium excessively lost out of sight. The reversibility issue which is the fundament of the weighting set of Paper V (as well as possible equivalent figures elsewhere) must, at a very minimum, be part of the equation when analysing impacts to the environment. To which degree simply depends on how underestimated this perspective is.

# CHAPTER 3. PRESENTATION OF SUPPORTING ARTICLES

In the following, the five papers connected to this project will briefly be presented.

The CCS case forms some of the underpinning for the project, but the weighting scheme is nevertheless not tailored only for this technology: it fits any LCA case. Nevertheless, one continuing concern has been to ensure that the outcome is relevant to the strategic sustainability dimension which is involved in the choice between energy technologies.

As the articles have been written during the course of the project, they can be understood to belong to different stages on the path to, hopefully, increasing insight. Paper I reflects the first stage, in which weighting was understood as a more or less mystical, and primarily value-based phenomenon. It describes one possible way out of the moral relativism towards weighting which appears to be recommended by ISO 14044: sustainability and weighting are “wider” issues, not particular, well-defined and well-understood systems, and may thus require inquiry at a higher level of construal, as defined by e.g. construal level theory.

Ultimately, however, this psychologically based understanding of weighting is challenging to further develop into tangible weighting factors. In order to establish more “hard facts”, Paper II reviews already established criteria in LCA literature for evaluating whether or not a weighting method is “good”.

On the basis of this, Paper III defines and establishes Arctic scaling factors in the context of LCIA. Assuming that current weighting methods are sound and refer to the European region, these factors can simply be multiplied by indicator scores for each impact category, in order to reach a more regionally relevant result. The factors are based on a survey submitted to Arctic scientists, in which the “broad perspective” logic of Paper I was the main inspiration.

It was observed, however, that the responses of the survey reflected somewhat conservative estimates, which could probably only from a very pragmatic point of view be assumed to be indicative of what happens in the environment. Paper IV searches to overcome such survey biases and to identify generic weighting factors instead based on some form of “quasi-objective” data. Paper II is used to identify where to look for data, and Paper V then details the final gathering of data, from literature sources. The result in Paper V is a set of generic endpoint weighting factors. These could be used alongside the Arctic scaling factors identified in Paper III, although the latter at least from one particular perspective are likely to be of a more questionable quality.

In the following, this and more is described more in detail, on the basis of each individual paper.

## 3.1. PAPER I: THE PROCESS OF HANDLING AN EXCESS OF COMPLEX AND INTERDISCIPLINARY INFORMATION IN A DECISION SUPPORT RESEARCH SITUATION

Chapter 1 explained how a large number of topics can be relevant to LCA weighting. Particularly when there is a need to question assumptions, it is not immediately obvious what can be dismissed as irrelevant information. The author's early attempts to explore the topic of weighting in search of some form of meta-methodology more or less turned out to become explorations of "everything" that conceivably could have interest. Findings were often interesting, but often had a character of being too detailed and trivial. To some degree, this exploration recalled the "postmodern condition" described by Lyotard (1979/1984): the work that was performed could not always be summed up by much of a meta-narrative. Paper I outlines a road map which can guide a scientific decision support process from this confused patchwork of different information via a process of generalisation.

Over the earlier stages of the project, a pattern or principle emerged as to which information would turn out to be more relevant. Weidema (2009) calls this principle "the level of abstraction" required for weighting. The search for data relevant to weighting apparently required an approach where information at a high, not detailed, level of abstraction was favoured. Several attempts were made to document this observation by means of existing scientific and philosophical theories. For instance, the "is-ought divide" of David Hume (Black 1964) to some extent touches upon the observed trend: normative judgment cannot, seemingly, be empirically observed directly, in the material world; it requires some other level. Plato's "allegory of the cave" was also seen to be somewhat relevant to the issue (Plato 380 BCE/2012, 514a-520a). Moreover, the philosophical Problem of universals, whether universals or some form of wholes can be seen to exist or are mere words, appeared to be of significant relevance (Pap 1959; Occam 1323/2012, Book 1, Ch. 35; Aquinas 1274/1948, I, Q. 84-89; *cf.* General System Theory: von Bertalanffy 1969). Also, it was judged that if the cause is always "greater" or "more excellent" than its effect(s) (as perhaps presaged by thermodynamics provided equilibrium and an absence of particular non-linearity; see also Lloyd 1976; Aquinas 1274/1948, I-II, Q. 66, A. 1), a distinct form of causal hierarchy would emerge. If true, an inquiry into causes rather than effects would provide more principal and less scattered and detailed, albeit retrospective information. This recalls Neoplatonism's insistence that oneness [of a certain kind] is a cause which is preferable [in a certain manner] to coincidence.

Unfortunately, whereas these concepts can be enlightening, within a scientific context they can also add a layer of mystification and controversy, and did not provide apt means for further fruitful characterisation of weighting in the context of available journals. They are philosophical concepts, and lead to philosophical discussions – and after all, the final aim of the project is to develop tangible numerical factors of relevance to a real-world methodology and case.

Aiming at a more empiricist fundament to weighting, the paper assumes that the level of abstraction referred to by Weidema (2009) is relevant to weighting, and outlines what this concept can be understood to encompass. Let us briefly summarise how it is relevant. It is known that as we move from left to right in figure 1, the scientific basis for the calculations becomes less clear-cut: to a larger extent, estimates, broad indicators and stereotypes are applied. Hence, there is an increasing deviation from "the exact sciences". The moral dilemmas involved in each step also become more overt. When weighting at endpoint, you are actually expected to rate the relative value of ecosystems, humans and resource availability against each other. As outlined in the above, this is an unusually large and difficult moral dilemma. As a result, weighting trade-offs must be based on some very roughly estimated overarching principle, unless it tacitly or explicitly aims to take into account only part of the dilemma. This is what is meant by "level of abstraction": information that eventually is *relevant* to weighting takes the character of broad, "high-level" estimates or indicators. These estimates summarise a broad range of information. A "low level" of abstraction concerns more specific and tangible information. (A computer scientist will spot a connection between levels of abstraction and the distinction between low-level and high-level programming languages) However, in this context "high-level" does not necessarily mean "advanced" or "good": while *relevance* of high level concerns to weighting can be established, it is not immediately clear whether such "high-level abstractions" form *valid* input to LCA weighting, as weighting is partly a normative undertaking.

It was discovered that relevant terminology, as well as a body of relevant empirical investigation, on abstraction level has been developed within the field of Construal level theory (CLT), from the field of social psychology. As the article outlines, a high level of "mental construal" is relevant to the scope of weighting, whereas a low, detailed level of construal is connected to less general information. These definitions provide a starting point for illuminating the normative pros and cons of weighting by means of observations from previous empirical studies.

CLT provides a tool for identifying whether data can be said to be at a relevant "level of abstraction". It can also be used to enhance understanding of "framing", or the context provided to weighting judgment. This is a previously somewhat unexplained element which has been shown to influence weighting factors (Mettier et al. 2006; Mettier and Scholz 2008; Myllyviita et al. 2013). Goedkoop et al. (2013-2) describe framing like this (p. 36):

*Panels tend to give a small range of weights (usually between 1 and 3). In social sciences, this is called 'framing', and is a problem in both endpoint and midpoint methods*

Here, however, framing refers not only to this small range, but to the full and, it would seem, unavoidable context of such delegated weighting tasks.

The paper argues that decisions made for a very specific context or without contemplating a "holistic" perspective may lack perspective. It proceeds to show how an "informaiton overload" at the specific level can be overcome by a six-step procedure which involves increasing the level of abstraction in order to further more holistic understanding, and then decreasing it in order to further implementation and communication. The model is suggested as one possible way of escaping a maze of complex information, but it does not exclude the possibility that other ways can be possible too.

A high and a low level of construal can further be connected to two terms from *Holism and Evolution* by Smuts (1927, p. 20-21), "error of analysis" and "error of abstraction". Whenever we analyse something in-depth, we tend to leave the big picture, the *whole*, out. This reductionism forms the "error of analysis". Similarly, when we take a holistic point of view, we have to make what Smuts calls an error of abstraction, because every *detail* is not taken into account. LCA weighting can be connected to both the error of analysis (particularly for the case of weighting by proxy, see Ahlroth 2011) and the error of abstraction, but perhaps typically the latter if an attempt is made to avoid weighting by proxy and capture the big picture, in the process for the moment forgetting details of lesser importance. In turn, construal level theory provides concepts required in order to understand how analysis and the generalisation involved in abstraction can be seen as fundamentally different.

In sum, even if the validity of abstraction is not obvious, Paper I presents an ideological underpinning for complex, interdisciplinary projects in general and weighting/valuation in particular. The fundamental idea of increasing the level of generalisation in order to reach a higher level of understanding to some extent formed a basis for the rest of the project. The requirement for the inquiry into methodological issues was the holistic perspective described in the article, not really narrow analysis starting from well-defined terms and a perfectly rigid methodology. A process which has this form of holistic starting point is not straightforward to document, perhaps particularly not if the audience consists of engineers who may be used to reasoning using analytical, not holistic terms as defined by Smuts. Put in another way, scientists tend to shy away from generalisation and stereotypes, and tend to seek more detailed and accurate assessments whenever generalisations are put forward. However, LCA weighting can be said to be generalisation about environmental damage and the creation of stereotypical conclusions about the environmental performance of products and processes.

As the article points out, contemplation of or reasoning at an abstract level is required in order to reach a holistic overview. This is illustrated with a quote from Jan Smuts,

> “The abstract thus becomes the real, the concrete is relegated to a secondary position. This inversion of reality is very much the same procedure as was followed by the scholastic and other philosophers who attributed reality to universals instead of to concrete particulars.”

It should be noted that the idea that the abstract can in fact become as real as details is a stance which is in contention in philosophy: some will agree, some will not. This problem is called the Problem of Universals. One problem involved with rejecting universals altogether is that terms such as “holism”, “sustainability” and “environment” may lose their meaning. The opposites defined by Smuts and mentioned in the article, “error of analysis” and “error of generalisation”, may serve to illuminate how generalisation and stereotyping can have certain virtues and not only be a liability in every case.

An acceptance of the existence of abstraction levels as well as a willingness or tendency to accept higher levels of abstraction may – perhaps – be indicative of either a “fatalist” or a “hierarchist” worldview as defined by grid-group typology (Douglas 1973/1996, ch. 4); these perspectives are further treated above as well as in Papers IV and V. Abstractions typically (although not necessarily) lead to categories which are less specific to an individual and more commonly shared. This corresponds to more “grid” in the grid-group typology framework. This vaguely indicates that any form of standardised or generalised weighting procedure, as well as weighting sets which unquestioningly are used over and over, might appeal less to “egalitariatist” and “individualist” perspectives. According to the definitions of Douglas (which may of course also reflect a perspective), the latter two groups would probably recommend an approach that to a larger extent than readymade weighting sets take into account the diversity of conceptions surrounding the topic. Whereas these stereotypes are not by any means definitive, as also pointed out by Hofstetter (1998) and Grendstad et al. (2006), egalitarianists might thus be expected to prefer an avoidance of weighting and rather complement un-weighted LCA results with a thorough qualitative investigation of the relevant decision context, as well as an investigation of the assumptions inherent to the calculation methodology. At least in Norway and the Nordic countries, the ground of qualitative investigations which aim to show diverse facets of a case and its decision contexts is to some extent covered by qualitative methods such as Environmental Impact Assessment (EIA) and by a democratic structure which traditionally has allowed a comparatively large degree of bottom-up power.

One early comment by a reviewer stated that if weighting should reflect a broad sustainability measure, one should simply define this principle for sustainability, and then derive weighting factors from that starting point, directly and without involving opinions and socio-psychological concerns. Of course, a disadvantage is that such an approach removes the inclusion of societal values in weighting, which can be seen as a check and balance for retaining a minimum of human reason in the final LCA result, and which was one of many recommendations identified in Paper II (see also section 2.9). In addition, it is not obvious how to identify a consistent and ethically acceptable principle for sustainability which is also holistic enough for the purpose of weighting. Nevertheless, in articles IV and V it was decided to develop weighting factors from this starting point: Paper IV presents a justification for this choice. A general broad perspective was pursued in Article III. The difference between these two approaches was also discussed in chapter 1, and will be further highlighted in the evaluation of section 2.9.

## 3.2. PAPER II: REVIEW OF CRITERIA FOR EVALUATING LCA WEIGHTING METHODS

Of the five articles, this was the most traditionally empirical article, as it did not aim for the ethical interpolations and broad-ranging discussions of the other articles. As pointed out in the introduction, the project required some form of understanding of what "good" LCA weighting really is. As the state of the art of LCA in regard to this question seemed to at least to some extent be dominated by confusion justified by the subjectivism criticised in chapter 1, it was assumed that this topic would be of interest also to a wider audience independently of this PhD project. The scope of the article was to identify and collect previously published conceptions about what LCA authors have perceived as good schemes for LCA weighting. The starting point for the literature search was the term "criterion", pl. "criteria", hence the title "Review of criteria for evaluating LCA weighting methods".

Influenced by the observed difference between the "abstract" high level and "concrete" low level of construal investigated in Paper I, it was found that sets of criteria in LCA literature could be classified into two types. The first of these types consisted of "abstract" criteria, which primarily recommended criteria for weighting schemes at the level of ideas. For instance, these criteria recommended features such as transparency and reproducibility, and that the method pursued should be practical and also comprehensive.

The other type of criteria was classified as "concrete", as they were more linked to "how" to perform weighting. These criteria turned out to suggest tangible opportunities for what could be used as input to "good" weighting schemes. The concrete criteria turned out to be very useful later; this is documented in Paper IV. It should be pointed out that the article does not distinguish between the different forms of weighting described in section 1.1.3. This aspect of the concrete criteria was investigated in Paper IV.

The general criteria are applied to other findings of this project in section 2.10.

## 3.3. PAPER III: BRIDGING ARCTIC ENVIRONMENTAL SCIENCE AND LIFE CYCLE ASSESSMENT: A PRELIMINARY ASSESSMENT OF REGIONAL SCALING FACTORS

As outlined in section 1.2, the Arctic environment is extremely complex. It cannot be satisfactorily summarised in one article or by any set of factors. The scope of the inquiry documented in this paper is therefore to pragmatically improve weighted scores in LCA for Arctic conditions, not to fully comprehend this environment and to fully communicate such perfect understanding through factors.

It is not obvious how to develop normalisation factors for the Arctic region, because a large part of the environmental impact to this region stems from emissions in other regions that cross regional borders (see *e.g.* AMAP 2002, pp. 9-22). This is the case for, for instance, persistent organic pollutants (POPs) and mercury, which presently are huge environmental concerns in the Arctic. An alternative would be to use country-specific factors (for Russia, Canada, Norway, etc.), but this would not capture the essence of the Arctic case in a satisfactory way. A lack of normalisation factors makes several of the established weighting approaches unavailable. Certain other approaches, such as weighting sets based on distance to target, would also be difficult to develop for the Arctic region due to data availability concerns. Also, any development of a full new set of impact and damage characterisation factors for the Arctic region would be very time-consuming. Because of this, the approach chosen was to use LCA characterisation/weighting in a "standard" region as a benchmark to be adjusted by a simple set of regional scaling factors. This implies that the weighting factor for each impact category would be "scaled up" to Arctic conditions by a simple multiplication with a respective regional scaling factor.

It was decided to investigate the priorities of Arctic scientists and researchers to the Arctic environment. These experts were presumed to be more likely to possess knowledge about the somewhat technical terms involved in the study, such as eutrophication, acidification, *etc.* Parts of the general public may never have heard of these terms, which would probably render a study with this group as a target group meaningless.

The scope of this paper was threefold. A survey was submitted to individual researchers, both in order to observe their priorities between known environmental categories from LCIA, and their suggestions for other categories. In addition, Arctic environmental science at a collective level was investigated by looking into the key issues highlighted by AMAP's Assessment Reports.

Individual experts were asked to quantify regional scaling factors for the Arctic. Regional scaling factors is a term which was initially used by Tolle (1997), but the definition in this article is somewhat different. Paper III investigates the interregional difference between the Arctic and a reference region which reflects current LCIA methods: chosen to be "Europe", as this is the reference region for most "site-generic" methods in ReCiPe 2008, see Goedkoop et al. (2013, p. 4). The experts were asked to assess the relative severity of impact and damage categories (from LCIA methods Stepwise 2006 and ReCiPe 2008) between the two regions. If the respondent reported a factor higher than 1, it would be expected to communicate that this respondent perceived the category to be more severe in the Arctic than in Europe. A reported factor of 3 for, say, acidification, would thus be equivalent with the statement "Acidification is 3 times more severe in the Arctic than in Europe". As explained in section 1.1.4 this statement is, however, ambiguous, because it first can refer to the current monitored state of affairs, whether acidification is currently an observed problem in general terms, and second to the vulnerability of the region to acidification. The latter is more consistent with the impact assessment scope of LCA. To the extent that it was possible, this point was explained in the survey, and respondents were asked to favour the impact assessment perspective. Inspired by the need to focus on the total picture and not just for instance one or two issues relevant to the respondents' own research – *cf.* Paper I, respondents were also asked to have a broad perspective on sustainability in mind. This wish to avoid too fragmented analysis was also the reason for not dividing the regional scaling task into several sub-tasks modules in the vein of MCDA (*e.g.* Soares et al. 2006).

The level of approximation required from the respondents is very large. Also, as the researchers are not LCA experts, they could not be expected to know the difference between and fully distinguish between impact characterisation, damage characterisation, normalisation and weighting. Whereas the eventual responses can be used to scale site-generic midpoint and endpoint weighting factors to Arctic conditions, such precise use may also involve a relatively rough approximation. On basis of the experiences in Paper III, Paper IV criticises the employed "open-ended" quantification: it can lead to conservative numerical estimates due to a wish to not ruin the study with "extreme" numbers. This would make the final results deviate too little from the benchmark. Also, it is not transparent how the researchers reasoned when they came up with the figures, and it is therefore difficult to construct much of a criticism of the result. To some extent, the survey is an attempt to force researchers into making some of the "cold-blooded" trade-offs and interpolations required in LCIA, and to bring simplicity and clarity into what is known to be opaque, unclear and extremely complex. Asking for such overarching data was somewhat unpleasant from a scientific perspective, because it would be obvious that the rough estimates would not even come close to the actual truth (*cf.* the "thing in itself" problem described in section 1.1.3). Due to these issues, a low number of responses were expected, and a low number of responses were also received.

It was decided against trying to force a larger number of responses: the scarcity of data was rather accepted as part of the findings. Results were reported as confidence intervals, and a low number of responses mathematically increases such intervals' range. Some non-respondents probably refused to respond both because of the complexity of the underlying issue, and because they perceived the survey as an attempt to oversimplify this complexity (there were indications that this was the case in some of the communication with eventual non-respondents, although this was never investigated in a structured manner). The final result of their decision difficulty or non-cooperativeness is a wider confidence interval, *i.e.* higher uncertainty in the final numbers. Hence, the "uncertainty" of non-responding researchers seems to have caused corresponding uncertainty in the results.

In sum, Paper III explores and illuminates some of the overarching picture of the Arctic environment. As explained, this cannot be done in an ultimately satisfactory way, and at least not within the scope of only one article. The quantitative results and the ensuing discussion should not be regarded as "the final truth" about the Arctic environment, but as an indication of what is important. The median values reported could of course be used in LCAs from a pragmatic point of view, but the limitations involved should in that case be fully explained. Wherever more specific regional characterisation factors exist (for instance, for the case of Norway, acidification characterisation factors for Norwegian conditions) these could be employed instead of the Arctic scaling factors.

## 3.4. PAPER IV: WEIGHTING IN LIFE CYCLE ASSESSMENT (LCA) BASED ON EXTERNALLY IMPOSED RESTRICTIONS: SLOWNESS OF REVERSIBILITY OF DAMAGE AS AN INDICATOR OF ENVIRONMENTAL VALUE

As explained in section 3.1, a reviewer recommended that weighting factors be developed from a principle of sustainability rather than from opinions based on a "holistic mindset". The problem with this recommendation is that any unifying principle does not seem to exist, and at least not at the required level of abstraction. It could indeed be questioned whether such a principle ever can be devised.

Nevertheless, this article explores how such "externally imposed restrictions", which in turn may be linked to the "limits of growth" concept of Meadows et al. (2004), can be relevant to weighting. It involves an careful definition of weighting and the relation to normalisation, as well as an an overview of how values relate to LCA. These clarifications make it possible to discuss weighting without lapsing into false disagreement (or false agreement) due to confusion over terms, as described by Næss (1982).

From an investigation of the concrete criteria in Paper II, one finding in Paper IV is that *reversibility* and the *substitutability of the damaged item* are two principles for "good" weighting from literature which at least apply to endpoint LCA weighting without prior normalisation. If a safeguard subject (or damage category) is not substitutable for anything else, it somehow belongs to a sphere of "invaluable" objects (or, subjects) that are of relevance to LCA endpoints. And next, a subject's regeneration rate can be seen as a measure of its reversibility. Hence, its inverse, the regeneration time of the safeguard subject, is a measure of its irreversibility, which is assumed to be an indicator of its proper weighting factor.

The article observes that if a safeguard subject is not substitutable for anything else, if there is or should be a taboo connected to its use, then it should perhaps never be damaged. And, if it nevertheless be damaged, the group of safeguard subjects (the damage category) must at the very least be allowed "rest", *i.e.* time to be fully regenerated or "replenished" after the damage. This paints a very simplified, but at the same time extremely concise picture of sustainability. The function of a weighting scheme based on regeneration time will not be completely opaque (as the case is with subjective judgment, such as the factors in Paper III). Hence, there is more transparency involved. Once the traditionally opaque weighting step is more transparent, transparency is actually also increased for LCA in general, and gives some indication as to what it actually measures. Regeneration is a complement to damage, and thus provides some consistency to the logic of LCA. This functional approach also provides an opportunity to see what LCA weighting and by extension LCA does *not* take into account. While the environmental damage, the wait for subsequent regeneration – as well as every impairment which is not counted – can be seen as a tragedy or perhaps as "environmental depression", a somewhat curious observation is that the eventual modelling of a "happy ending" (regeneration) makes the narrative of LCA into a form of "comedy", in the classical sense of the word. (At the same time, the terminology of scientific writing tends towards understatement when deascribing violence and casualties, and "environmental insult" may thus in most cases suffice as a term to describe the tragedy involved; it is, however, a potential communication problem that this term conveys a euphemised rather than a realistic picture of events.)

Importantly, "externally imposed restrictions" (not necessarily only the two identified) may be an important class of input to large-scale policymaking and strategic decisions. As outlined in the above, to rest pioneering decisions such as whether or not to implement CCS on mundane observations and opinions would in a particular way entail "putting the cart before the horse". The approach highlighted in this article provides a certain degree of innovation to the equation, and is of particular relevance to the case of the project.

Perhaps interestingly, Paper IV also contains a brief description of post-modern science, grid-group archetypes, and the concept of "prudence".

## 3.5. PAPER V: WEIGHTING IN LIFE CYCLE ASSESSMENT (LCA) BASED ON EXTERNALLY IMPOSED RESTRICTIONS: DEVELOPING ENDPOINT WEIGHTING FACTORS BASED ON REGENERATION TIME

This article develops actual endpoint weighting factors for the ReCiPe 2008 LCIA methodology (Goedkoop et al. 2013) from the principle presented in Paper IV. (These factors could also be hooked onto other characterisation methods after some recalculation.) The most significant challenge stems from resource depletion, because the regeneration of the safeguard subject is related to economic growth, which is not entirely stable over time. The eventual set of weighting factors is based on an assumption that we can extrapolate current economic growth into the future, but this will not necessarily prove to be true. Also, whether resources which are currently regarded as non-substitutable will also be so in the future is not immediately obvious. It is also not obvious that there should be a “taboo” connected to metal or fossil fuel depletion, the two resource categories covered by ReCiPe’s damage characterisation. In addition, the causal links between the different damage categories may in the long term be complex and significant – for instance, further ecosystem damage will according to Rockström et al. (2009) have adverse effects on (or even pose existential threats to) humans. Also notwithstanding the other numerous simplifications and assumptions made when developing this scheme, the weighting set provides a reasonable answer to the weighting question. As assumptions are to a large degree transparent and the quantification to a less extent than that in Paper III relies on opaque human guesswork, the weighting approach can quite easily be understood and further developed.

In conclusion, the logic of Papers IV and V is that environmental *damage* does not provide a full measure for the environmental “depression”, “gravity” or “tragedy”: in order to assess the latter, one has to consider both damage and the subsequent regeneration. Not considered by the articles is the important justice perspective: who should be allowed to inflict environmental insults onto whom, and for which purposes. The weighting set can also be employed for other endpoint-based LCIA methods than ReCiPe 2008, although this could require some recalculation in order to reach correct endpoint units – see caption of figure 1.

Thus, this paper in conjunction with Paper IV provides weighting factors applicable to the CCS case for global conditions, whereas Paper III provides regional scaling factors for the Arctic. Papers I and II have contributed to by illuminating what weighting is, whether it should be performed at all, and how it may best be performed and validated. Next, the abstract criteria from Paper II (Johnsen and Løkke 2013, table 1) will be used to investigate the developed approach.

## 3.6. ANALYSIS OF APPROACH BY MEANS OF THE REVIEWED "ABSTRACT CRITERIA" FOR WEIGHTING

In table 1, the abstract criteria for weighting methods identified in Paper II are used to analyse the approaches of Paper III and Paper IV/V. The Arctic scaling factors are not properly speaking a weighting scheme in absolute terms, but a relative, regional adjustment or comparison of LCIA/weighting factors. As their scope nevertheless is similar, the criteria of Paper II may serve to illustrate these factors as well.

*Table 1. The methodology of Arctic scaling factors (Paper III) and the generic weighting scheme (Paper IV and V) in view of the abstract criteria from Paper II. Note that the table encompasses several pages*

| Criterion | Arctic (Paper III) | Weighting scheme (Papers IV and V) |
|---|---|---|
| Completeness/Comprehensiveness | Depends on the comprehensiveness involved in the judgment measured | "Myopic" focus on one indicator, but this particular indicator is wide-ranging |
| Include inter-effect weighting | No, this ground is exclusively covered by the weighting scheme | Yes, a degree of inter-effect weighting arises from the use of the same consistent principle across damage categories |
| Flexibility to include new problems | Yes, scaling factors can easily be connected to future developments within site-generic LCIA | Yes, provided that data on regeneration time is available |
| New value choices and characterisation methods can be included | Yes | Value choices: The methodology is fixed, but extremes and uncertainty can be explored. New characterisation |

| | | |
|---|---|---|
| | | methods can be added if appropriate regeneration data is available |
| Possibilities for further development | Opinions are not transparent, and cannot be further developed. However, the paper as a whole can be used as background information for further development | Yes. As the weighting scheme is transparent and functional, it allows more modules to be attached to it. Regeneration time estimates can improve with more knowledge |
| Practicality | Yes, opinions are feasible to measure, although opaque framing effects complicate the picture significantly if considered | Yes, regeneration time is feasible to measure |
| Presentation | The arguments behind the priorities are not transparent | The function of the weighting scheme can be presented |
| Reflecting the subjectivity of weighting | Yes, but the group of people that possesses knowledge about the full issue is small | Only to the extent that criticism of the methodology itself is viable |
| Geographic and temporal representativeness | Yes, this is the point of the approach. However, only rough approximations have been made for the definition of regions | No. This scheme is intended to be independent of time and space. Geographic representativeness is approached through the Arctic scaling factors. |

| | | |
|---|---|---|
| Feasibility | Yes, opinions are feasible to measure, although opaque framing effects complicate the picture significantly if considered | Yes, regeneration time is feasible to measure |
| Low requirements on amount of data | Yes | Yes |
| Good availability of data | No, not many people have relevant knowledge, and their competence is not necessarily readily available | To some extent yes, as regeneration time is an objective dimension, although Paper V shows that it is not all that simple |
| Low requirements on technical skills | Yes | To some extent |
| Low efforts needed for the execution | Yes | Yes |
| Content | There is no guarantee that the measured preferences are of “high value”; there is no yardstick for how to criticise responses | The content is relevant to weighting, but other indicators could also be important |
| Fairness | Depends on the people consulted | Yes, the cross-category consistency is an indicator of fairness. Chapter 5 points out |

| | | |
|---|---|---|
| | | that consistency can still be improved |
| Goal acceptability | Unknown, as the goals of respondents are not transparent | Yes, at least to some extent |
| Acceptability of category of weighting method | Depends | At least to some extent acceptable, unless one insists that weighting is only about incorporating held human preferences |
| Follows established standards for LCIA | Does not clearly distinguish between characterisation and weighting | As described in Paper IV, although it relies on objective data, it nevertheless reflects the subjective nature of weighting at another level |
| Adequate representation of values | Depends | Depends |
| Transparency | The methodology is transparent, but it is not transparent on which basis responses were made | Yes, the function of the scheme is transparent, and the background provided is comprehensive |
| Objectivity | No, unless researchers contacted retained this dimension | Yes |

| | | |
|---|---|---|
| Reproducibility (or Repeatability) | Not tested: As shown in Paper IV, framing effects could significantly influence the outcome | Yes |
| Relation to available and “best available” characterisation methods | Relates to ReCiPe 2008 | Relates to ReCiPe 2008 |
| Goal consistency | Depends on respondents | Yes |
| Acceptable scientific practice in the sciences used | The holistic perspective aimed at (on basis of Paper I) is somewhat at odds with MCDA | Yes |
| Clear discernment of objective and subjective elements | No | Yes |
| Systematic approach | To some extent | Yes |
| Robustness or sensitivity | Depends on respondents | Yes |
| Consistent results and transitivity | Depends on respondents | Yes |
| Treatment of uncertainty | Yes, results are given as confidence intervals. The inclusion of a literature review provides some background for critical scrutiny | No. Although this could be accommodated (see Paper V), uncertainty is likely to be larger between rather than within methodologies |

In summary, in view of the criteria the approach of Papers IV/V appears to be more successful according to the criteria than that of Paper III. Particularly the functionality and transparency of the former gives it a good "score" for several of the criteria.

# CHAPTER 4. CASE: AMINE BASED POST-COMBUSTION CARBON CAPTURE AND STORAGE (CCS)

In this chapter, the focus moves to the case of carbon capture and storage (CCS), which was introduced in chapter 1, particularly section 1.3.

As described in the above, the case of amine based post-combustion CCS has provided a backdrop for some of the fundamental decisions that have been made during the course of the project. As the underlying reason for introducing this technology is sustainability in a broad sense (*cf.* chapter 1), LCA needs to at least take sustainability issues into account in order to have relevance to CCS. Hence the treatment of what a broad perspective on LCA weighting implies in Paper I, the illumination of what "good" weighting is in Paper II, the attempt to investigate the Arctic environment as a whole in Paper III, and the aim for a both consistent and comprehensive scope in Papers IV and V. To some extent, the logic of the case (large-scale strategic decision-making) has to influence the methodology, which can be a disadvantage, but eventually the weighting scheme developed is equally relevant to any technology or product.

This chapter will investigate the case of a natural gas fired power plant with amine based post-combustion CCS, on the basis of observations in the papers and during the course of the project. LCA weighting as outlined in Papers IV-V will be applied to available data on the case. First, a few qualitative observations surrounding classification and rebound effects will be presented. Whether these suggestions are of importance or not may be uncovered by future research; it is also to some extent illuminated by the weighting exercise, see sections 4.5 - 4.7.

## 4.1. CAN A TECHNOLOGICAL FIX ADDRESS A FUNDAMENTAL FLAW INHERENT TO TECHNOLOGICAL FIXES?

Arvesen et al. (2011) argue that CCS involves a form of technology optimism, and asks whether the perceived merits of this technology are based only on overly simplified models and first-order effects. A sobering observation in relation to CCS is that an extreme cumulative amount of anthropogenic $CO_2$ has been emitted to air over the last few centuries. Nonetheless, environmental damage from climate change is more often than not considered to be a future rather than a past or present problem. This indicates that the environmental damage caused by an emission of, say, a mere 1000 kilograms of excess $CO_2$ to air is quite limited. At the same time, it has been shown (section 1.1.2) that particularly cumulative ecosystem damage from climate change can become extremely extensive. Whether or not a CCS facility has to capture, transport and store unrealistically large amounts of $CO_2$ in order to pay off even only environmentally eventually depends on weighting. Can a technological fix be provided for a global warming which itself is a product of technology, or do we need to find a solution which to a larger extent is based on something novel? Can any form of heavy machinery, technology and mass production really have an "environmentally friendly" face at all? Sometimes, the answer to a problem can actually be to do something with the root cause (and simply relax more as proposed by Nørgaard 2013), not to frantically "build more stuff" in order to fix the symptom (through some form of $CO_2$ waste management). This assumes, however, that technological fixes are all equal, and that they are all bad – which ultimately is not very nuanced. Nevertheless, power plants with CCS must at some level be compared to the alternative of having or building no power plant at all. This should be possible within an LCA context.

## 4.2. STORAGE LEAKS ON LONG TIME SCALES

It was mentioned in section 1.3 that storage leakage is a significant public concern in connection to CCS. Due to the complexity of the underground, the rate of and eventual cumulative leakage are hard to predict. Despite extensive current focus on storage (*e.g.* Elenius 2011), leaks are apparently very challenging to model at long time scales (Dahle 2012). Consequently, it is not accurate to *completely* eliminate any risk of $CO_2$ leaks from the storage facility into inhabited areas. $CO_2$ is toxic at high concentrations, and this can theoretically be dangerous to human health. However, in most cases this can probably be prevented by proper planning, and also alleviated by monitoring and intervention, as detailed by DNV (2012, section 4.3). It is not within the scope of this thesis to evaluate whether this is a large problem or not: the author has observed that some geological experts claim that such a scenario is impossible or highly improbable and essentially a non-issue, whereas others grant that there is a theoretical, but small risk involved.

At a spatial resolution and level of precaution more relevant to LCA, it is more significant that some scenarios do not exclude significant leakage of the stored $CO_2$ over very long time scales (*i.e.* decades and centuries). Ha-Duong and Loisel (2009) recommend a goal of zero leakage, and point out how economists may accept leakage rates as high as 2% per year. Anything even remotely approaching the latter figure would of course be ubiquitous to include in LCAs of CCS. As demonstrated by Paper V, in order to fully comprehend the gravity of species loss, a vast time perspective is required. Hence, even if leakage from storage sites is much slower, if continuous and eventually extensive leakage is expected, it should not be regarded as outside the scope of LCA studies. Nevertheless, according to the LCA of CCS review of Corsten et al. (2013, pp. 62-63),

> In the reviewed literature, the vast majority of the studies only account for the pollutants emitted during power plant operation and do not take into account the effects of $CO_2$ leakage on the long term.

One example of the opposite is Viebahn et al. (2007), who perform a sensitivity analysis of the LCA results for different leakage scenarios. They observe (p. 127):

> In case of a leakage rate of 0.1%/a, the whole carbon dioxide stored in the underground would be released into the atmosphere within the next 6000 years.

Apparently, a significant difficulty in the development of LCAs of CCS is data availability on leakage rates.

## 4.3. RESOURCE USE

CCS may require significant use of metal for the purpose of pipelines for transporting gases. In addition, as also explained in section 1.3, there is significant underground fossil fuel depletion involved in power plants with CCS that use such fuels. At the same time, fossil fuel depletion for the purpose of power production with CCS denies the market access to these fossil fuels (see also section 3.5 on rebound effects). Less fossil fuel eventually available to the market would imply less global warming. This means that fossil fuel depletion in itself is currently desired from a climate change perspective. At the same time, such depletion may prove harmful to future generations.

As shown in Paper V, resource depletion is a damage category which is difficult to assign a rigid weight: such depletion could in practice be given everything from zero to infinite weight – see the discussion in Paper V. This paper nevertheless assigned resources a weighting factor based on a conjectured 3% future economic growth.

## 4.4. TOXICITY

The use of amines such as MEA in post-combustion capture processes has been connected to toxicity concerns that involve the formation of degradation products such as nitrosamines and nitramines. For an overview, see *e.g.* Karl et al. (2011) and Brekke et al. (2012, chapter 3). The latter report concludes, however, that the USETox model ranks formaldehyde as more important for toxicity than nitrosamines and nitramines for the case of an amine-based capture process.

## 4.5. REBOUND EFFECTS OF INCREASED POWER PRODUCTION

If a new gas-fired power plant with amine-based post-combustion CCS is built, it will increase the power produced in the region, thus lowering power/electricity prices. This will in turn lead to rebound effects (Hertwich 2005) or what Sathre et al. (2012, section 3.7) call market effects. If a power plant is built, the power/electricity output will be used for several purposes. These purposes will in turn cause emissions and environmental impact and damage. If the power plant is not built, this surplus impact/damage would perhaps not materialise at all. Perhaps at least from a consequential LCA perspective, this surplus impact/damage may have to be counted as, ultimately, the responsibility of the power/CCS plant. As this surplus impact will predictably be extensive, any increase in power production is probably unlikely to be recommended from a degrowth perspective (Nørgaard 2013).

Also, some CCS projects include enhanced oil recovery (EOR) in conjunction with the storage. In these cases, the production and eventual fate of the oil (*e.g.* in many cases combustion) may have to be modelled as part of the environmental responsibility of the CCS module.

## 4.6. WEIGHTING BASED ON A CCS CASE FROM LITERATURE

Modahl et al. (2012) illustrate four cases of power production by applying several Life cycle impact assessment methods. In the following, two of them will be investigated on basis of the findings of the Papers. The first is a reference case of a natural gas-fired power plant without CCS. The second (CCS-3) is equivalent, but includes both amine based post-combustion CCS and process integration. Note that the latter scenario reflects the construction of a new power plant with CCS, not an adaption of CCS to an existing power plant. The assumptions and methodology of Modahl et al.'s study are documented in the article. Note that, among other things, ozone depletion potential, area consumption, toxicity, storage leaks and material consumption and waste are not included in Modahl et al.'s study; the following treatment thus cannot take these issues into account.

Modahl et al. (2012, their figure 3) provide weighted LCA results by means of ReCiPe 2008, among other methods. According to ReCiPe, methodology, four impact categories dominate the results for both scenarios: Fossil fuel depletion, climate change ecosystems, particulate matter formation, and climate change human health. Of these, ReCiPe indicates that climate change forms the greatest concern in both. On personal request to the authors, the ReCiPe 2008 hierarchist endpoint results [*i.e.* LCA results characterised to endpoint, but not weighted], which form the basis of this diagram, were obtained. They are shown in table 2 for the reference scenario, and in table 3 for the CCS-3 scenario. Note that the numbers refer to 1 TWh of produced power.

*Table 2. Hierarchist ReCiPe 2008 endpoint results for the reference scenario (natural gas power plant without CCS), in accordance with Modahl et al. (2012). The functional unit is 1 TWh of power produced*

| Impact category | Unit | Total |
|---|---|---|
| Climate change Human Health | DALY | 553.30797 |
| Climate change Ecosystems | species.yr | 3.134056 |
| Ozone depletion | DALY | 0.00030257708 |
| Terrestrial acidification | species.yr | 0.00088483518 |
| Freshwater eutrophication | species.yr | 2.6461339E-5 |
| Human toxicity | DALY | 0.66804409 |
| Photochemical oxidant formation | DALY | 0.010942191 |
| Particulate matter formation | DALY | 18.883827 |
| Terrestrial ecotoxicity | species.yr | 2.9326718E-5 |
| Freshwater ecotoxicity | species.yr | 2.7913018E-5 |
| Marine ecotoxicity | species.yr | 6.5843463E-6 |
| Ionising radiation | DALY | 0.0027359079 |
| Agricultural land occupation | species.yr | 0.00029241176 |
| Urban land occupation | species.yr | 0.0011756481 |
| Natural land transformation | species.yr | 0.0010865335 |
| Metal depletion | $ | 87713.702 |
| Fossil depletion | $ | 487750.28 |

*Table 3. Hierarchist ReCiPe 2008 endpoint results for the CCS-3 scenario (natural gas power plant with amine based post-combusion CCS and process integration) in accordance with Modahl et al. (2012). The functional unit is 1 TWh of power produced*

| Impact category | Unit | Total |
|---|---|---|
| Climate change Human Health | DALY | 126.93218 |
| Climate change Ecosystems | species.yr | 0.71893265 |
| Ozone depletion | DALY | 0.0014026685 |
| Terrestrial acidification | species.yr | 0.0023156668 |
| Freshwater eutrophication | species.yr | 6.9633988E-5 |
| Human toxicity | DALY | 1.976646 |
| Photochemical oxidant formation | DALY | 0.013768368 |
| Particulate matter formation | DALY | 30.485522 |
| Terrestrial ecotoxicity | species.yr | 0.00034351951 |
| Freshwater ecotoxicity | species.yr | 0.00011512954 |
| Marine ecotoxicity | species.yr | 1.3872837E-5 |
| Ionising radiation | DALY | 0.012589257 |
| Agricultural land occupation | species.yr | 0.00083709224 |
| Urban land occupation | species.yr | 0.0017828175 |
| Natural land transformation | species.yr | 0.0022916952 |
| Metal depletion | $ | 139953.14 |
| Fossil depletion | $ | 801447.99 |

Tables 4 and 5 show calculated weighted indicators (another term is weighted scores) for each of these categories, and their relative contribution to the full "environmental insult". The key impact is emphasised in bold.

*Table 4. Weighted results, reference scenario. The principal category in bold. (Note that , is a decimal mark in the two rightmost columns)*

| Impact category | Endpoint unit | Endpoint indicator | Weighted indicator (yr^2) | Share (%) |
|---|---|---|---|---|
| Climate change Human Health | DALY | 553.30797 | 3,26452E-06 | 3,06016E-05 |
| **Climate change Ecosystems** | **species.yr** | **3.134056** | **10,6557904** | **99,88746843** |
| Ozone depletion | DALY | 0.00030257708 | 1,7852E-12 | 1,67345E-11 |
| Terrestrial acidification | species.yr | 0.00088483518 | 0,00300844 | 0,028201138 |
| Freshwater eutrophication | species.yr | 2.6461339E-5 | 8,99686E-05 | 0,000843366 |
| Human toxicity | DALY | 0.66804409 | 3,94146E-09 | 3,69473E-08 |
| Photochemical oxidant formation | DALY | 0.010942191 | 6,45589E-11 | 6,05176E-10 |
| Particulate matter formation | DALY | 18.883827 | 1,11415E-07 | 1,0444E-06 |
| Terrestrial ecotoxicity | species.yr | 2.9326718E-5 | 9,97108E-05 | 0,00093469 |
| Freshwater ecotoxicity | species.yr | 2.7913018E-5 | 9,49043E-05 | 0,000889633 |
| Marine ecotoxicity | species.yr | 6.5843463E-6 | 2,23868E-05 | 0,000209854 |
| Ionising radiation | DALY | 0.0027359079 | 1,61419E-11 | 1,51314E-10 |
| Agricultural land occupation | species.yr | 0.00029241176 | 0,0009942 | 0,009319639 |
| Urban land occupation | species.yr | 0.0011756481 | 0,003997204 | 0,037469819 |
| Natural land transformation | species.yr | 0.0010865335 | 0,003694214 | 0,034629592 |
| Metal depletion | $ | 87713.702 | 3,50855E-08 | 3,28892E-07 |
| Fossil depletion | $ | 487750.28 | 1,951E-07 | 1,82887E-06 |
| Sum | | | 10,66779504 | 100 |

*Table 5. Weighted results, CCS-3 scenario. The principal category in bold. (Note that the comma is a decimal mark in the two rightmost columns)*

| Impact category | Endpoint unit | Endpoint indicator | Weighted indicator (yr^2) | Share (%) |
|---|---|---|---|---|
| Climate change Human Health | DALY | 126.93218 | 7,489E-07 | 3,03102E-05 |
| **Climate change Ecosystems** | **species.yr** | **0.71893265** | **2,44437101** | **98,93081207** |
| Ozone depletion | DALY | 0.0014026685 | 8,27574E-12 | 3,34943E-10 |
| Terrestrial acidification | species.yr | 0.0023156668 | 0,007873267 | 0,318654045 |
| Freshwater eutrophication | species.yr | 6.9633988E-5 | 0,000236756 | 0,009582187 |
| Human toxicity | DALY | 1.976646 | 1,16622E-08 | 4,72004E-07 |
| Photochemical oxidant formation | DALY | 0.013768368 | 8,12334E-11 | 3,28775E-09 |
| Particulate matter formation | DALY | 30.485522 | 1,79865E-07 | 7,27964E-06 |
| Terrestrial ecotoxicity | species.yr | 0.00034351951 | 0,001167966 | 0,047270998 |
| Freshwater ecotoxicity | species.yr | 0.00011512954 | 0,00039144 | 0,015842734 |
| Marine ecotoxicity | species.yr | 1.3872837E-5 | 4,71676E-05 | 0,001909012 |
| Ionising radiation | DALY | 0.012589257 | 7,42766E-11 | 3,00619E-09 |
| Agricultural land occupation | species.yr | 0.00083709224 | 0,002846114 | 0,115190505 |
| Urban land occupation | species.yr | 0.0017828175 | 0,00606158 | 0,245329772 |
| Natural land transformation | species.yr | 0.0022916952 | 0,007791764 | 0,315355363 |
| Metal depletion | $ | 139953.14 | 5,59813E-08 | 2,26572E-06 |
| Fossil depletion | $ | 801447.99 | 3,20579E-07 | 1,29748E-05 |
| Sum | | | 2,470788381 | 100 |

As expected from the particular observations in section 1.1.2, climate change damage to ecosystems is by far the dominant endpoint category – not only for the case of "regular" natural gas-fired power plant, but also for the construction of a power plant with CCS.

Another observation is that the scheme rates human health damage and resource depletion as essentially completely unimportant compared to ecosystem damage for both scenarios. Ecosystem damage constitutes 99.99997% of the inflicted gravity or "environmental insult" for the reference scenario, and 99.99995% for the CCS-3 scenario. This is shown in tables 6 and 7.

*Table 6. Contribution to damage categories, reference scenario, in percent. (Note that , is a decimal mark)*

| **Reference scenario** | Weighted ind. | Share |
|---|---|---|
| Ecosystem damage | 10,66779143 | 99,99996616 |
| Human health | 3,37996E-06 | 3,16837E-05 |
| Resource depletion | 2,30186E-07 | 2,15776E-06 |

*Table 7. Contribution to damage categories, CCS-3 scenario. (Note that , is a decimal mark)*

| **CCS-3 scenario** | Weighted ind. | Share (%) |
|---|---|---|
| Ecosystem damage | 2,470787064 | 99,9999467 |
| Human health | 9,4059E-07 | 3,8068E-05 |
| Resource depletion | 3,7656E-07 | 1,524E-05 |

This is very easy to summarise in a diagram – see figure 7.

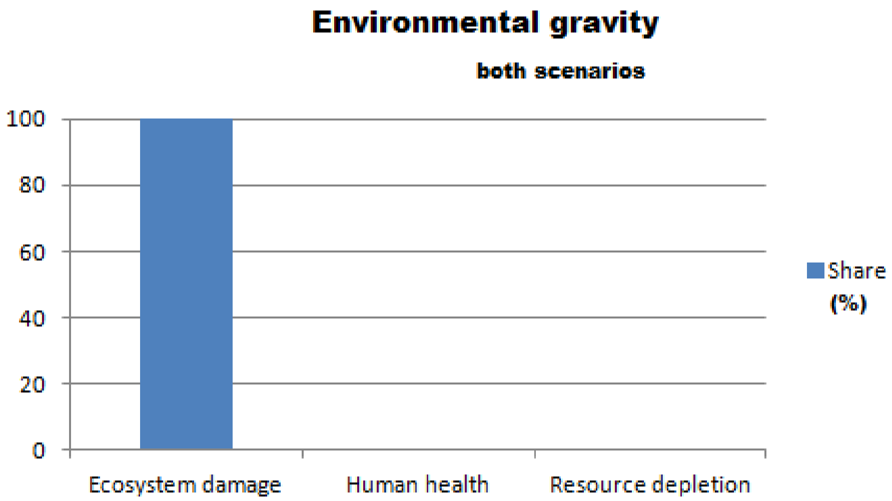



**Figure 7. Share of environmental insult (gravity) inflicted, by endpoint. Valid for both scenarios**

Figures 8 and 9 show the share of environmental insult or “tragedy” inflicted by midpoint. Again, the results paint a quite uniform picture.

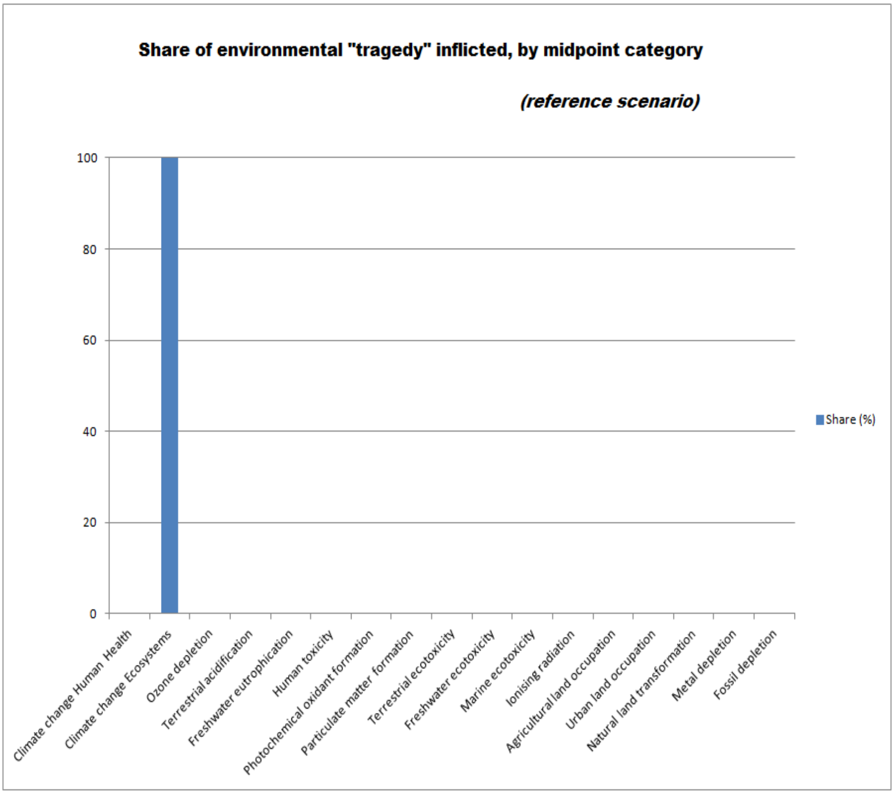
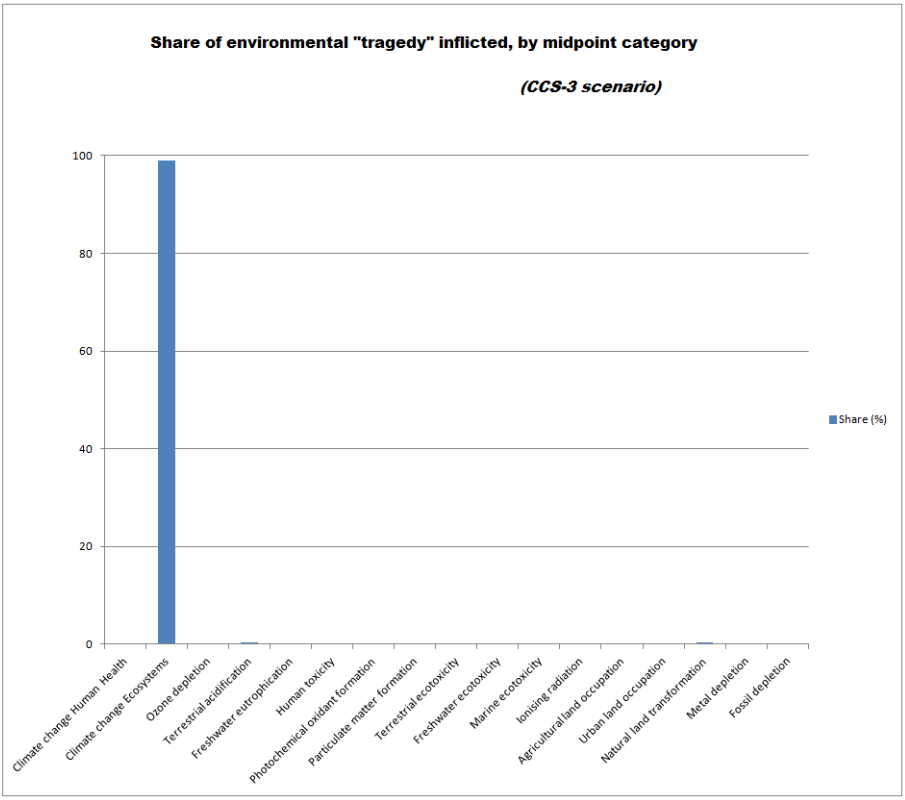



Figure 8. Share of environmental insult or “tragedy” inflicted, by midpoint. Reference scenario without CCS




## Figure 9. Share of environmental insult or "tragedy" inflicted, by midpoint. CCS-3 power production scenario

Now, all of these weighted results could next at least from a pragmatic point of view be adjusted by the Arctic scaling factors developed in Paper III, but this is omitted here as it would not make a significant difference to the big picture. This relative insignificance is in accordance with the observation in Paper IV on limitations involved in "intuitive quantification": it gives numerical results of a too narrow or conservative range, and in addition (or alternatively, because it) becomes too dependent on framing effects.

## 4.7. DISCUSSION

### 4.7.1. GENERAL OBSERVATIONS

A general answer to the question "is CCS desirable or not?" is not available from the results in section 4.6. It is obvious that the power plant with CCS fares better than the reference scenario which does not have CCS. The case does not look into the precise case of fitting CCS onto an existing gas-fired plant, but it can perhaps be conjectured that it will pay off environmentally in most cases. Also, it is not clear from the results whether a new gas-fired power plant with CCS is "environmentally friendly" if the benchmark is a corresponding scenario involving, respectively, wind power, nuclear power, wave power, solar power, *etc*. Moreover, it is worth pointing out that not constructing a power plant at all will normally be the best alternative.

The results should not be interpreted as a statement that resource depletion and human health concerns in relation to the case are insignificant. As we all know, these issues are indeed significant, and have halted or delayed several CCS projects. What tables 6-7 and figures 8-10 communicate is that global warming-induced damage to ecosystems, as well as general ecosystem concerns, *is even more important*. And, it is apparently virtually all-important for both cases. The global warming indicator, or even better, ecosystem damage, could have been used as proxies for total environmental importance in both cases without much error. This means that carbon footprints and (particularly) ecological footprints in a life cycle perspective could have been acceptable methodologies for assessing the environmental virtues of CCS, at least for the case of Modahl et al. (2012). For reference, Weidema et al. (2008) point out pitfalls and advantages involving the former. Huijbregts et al. (2008) analyse the latter in an LCA context, although on basis of characterisation and weighting by means of Ecoindicator 99, a precursor of ReCiPe 2008.

Of the issues that were hypothesised to be of importance to CCS in sections 3.1 – 3.5, the weighting exercise indicates the following:

- As global warming is the all-important *impact* category in the results above, the eventual cumulative $CO_2$ leakage from storage facilities will directly impact the final LCA results. This is also highlighted by Strazza et al. (2013, p. 1261). An analysis of leakage (*cf.* section 3.2) is not included in the results of Modahl et al. (2012); as pinpointed in section 3.2, this is a recurring weakness of LCA studies of CCS. Nor is toxicity concerns.
- In addition, the capture, transport and storage efficiency with regard to $CO_2$, as well as greenhouse gas emissions in the full life cycle, are apparently vital for the final results of at least the CCS-3 scenario. This is covered by the analysis of Modahl et al.

- The characterisation of ReCiPe which the results in section 3.6 are based on does not specify marine acidification. Such acidification is an indirect consequence of $CO_2$ emissions to air, and a direct consequence of leakage from off-shore $CO_2$ storage facilities to seawater. As global marine acidification, like global warming, is slowly accumulating in severity without being continuously or fully remedied by means of any mechanism, this omission could be vital to notice. Moreover, for the (Norwegian) Arctic off-shore case, local leakage/acidification events could hypothetically trigger significant ecosystem damage to species-rich coral reefs with a vast regeneration time, such as *Lophelia pertusa* (Davies et al. 2007; Direktoratet for naturforvaltning 2008). Nevertheless, whereas leakage from storage sites may or may not be a significant threat, it must be kept in mind that for a power plant without CCS, there is "100% leakage" to the air/ocean system. Whereas global warming is normally assigned more attention than marine acidification, it is not immediately obvious whether emissions of $CO_2$ to air or to seawater are more damaging to ecosystems. For the case of on-shore storage, Strazza et al. (2013, p. 1261) particularly recommend to take into account soil pollution from leakage.
- Consequential/rebound effects were not considered in the study, and could be of importance. Results may predictably change if enhanced oil recovery (EOR) is used and/or if increased power production (or oil availability) causes additional environmentally detrimental activities. This would impact total carbon emissions and ecological damage
- Resource use for the case of both metals and fossil fuels was assessed to be relatively speaking completely insignificant in both scenarios. Note, however, that resources are difficult to assign a general weighting factor, see Paper V
- Toxicity was assessed to be relatively speaking completely insignificant in both scenarios. Note that LCA studies in general do not take into account local conditions and occupational safety and health issues
- The results indicate that a natural gas-fired power plant with CCS is not a "zero-emission" technology. Undesirable side effects should be expected from any "technological fix to a problem inherent to technological fixes". The weighting schemes of both ReCiPe and Paper V indicate that total environmental gravity is not eliminated with a scenario involving process integration of CCS, but reduced by about 80%. As illustrated by Modahl et al. (2012), process integration of CCS may have a large impact on the final results

Importantly, note the limitations to the weighting scheme outlined by Papers IV and V (and to some extent, Papers I and II as well as chapters 1 and 2, and chapter 5 below.

### 4.7.2. DO THE RESULTS IMPLY AN ECO-CENTRIC WEIGHTING SCHEME?

Immediately, notwithstanding the analysis in section 2.9, an obvious emerging question when analysing the results is whether the weighting scheme overstates the importance of ecosystems. In Papers IV-V it was demonstrated that the scheme is not "eco-centric": on the contrary, it carelessly assigns zero value to the health and lives of individual animals. Only species survival is counted as important. On the other hand, the survival of the human species is not covered as a damage category. In fact, to put this into perspective, only if [a replacement of] every single species on the planet were recreated through evolution every single year would human health and resource concerns end up at a more or less similar general order of magnitude as that of ecosystem damage (ref. tables 6-7) – and that even goes for a power plant with CCS. It appears that the only way to make ecosystem damage and global warming less omnipresent in the final results is to *completely reject* the idea of regeneration time as a principle for weighting. If so, it can be pointed out that there is a finite number of species on Earth. At some point, the current decline in the number of species will have to stop.

Another point is that the weighting scheme could conceal the current observed decline in ecosystem quality: the current precarious and deteriorating situation (*cf.* the data presented by Rockström et al. 2009) is not taken into account at all. If it were, ecosystems could have been assigned an even higher value.

Perhaps the results can be a cause of faint optimism, as they *might* indicate that we are not engulfed by a horde of environmental challenges of the same scale as global warming – which, if we take into account the observations in section 1.1.2, would simply imply the forthcoming end of the world.

### 4.7.3. RELATION TO RECIPE 2008

The weighted single score indicator of the reference scenario is about 3.5 times higher than for the CCS-3 scenario with ReCiPe's weighting scheme (Modahl et al. 2012, figure 3). If we compare tables 6 and 7, this ratio is very comparable: it stands at 4.3. The main difference between ReCiPe and the regeneration scheme is that the former assigns ecosystem damage from global warming less than 50% significance for all scenarios, whether regeneration assigns it 99.9% significance for the reference scenario and 98.9% for the CCS-3 scenario. Even more noteworthy is the fact that ReCiPe considers human health (mainly from global warming and particulate matters) to have a significance of over 50% for both scenarios, whereas it constitutes 0.000031-0.000038% of the equation for the two respective scenarios provided the regeneration method. ReCiPe also assigns some importance to fossil depletion, whereas this is seen as equally unimportant by the regeneration perspective.

The ReCiPe normalisation/weighting methodology may not have been able to take into account the fragile nature of ecosystems. Weighting questionnaires are perhaps not the most foolproof way to make trade-offs, and (as pointed out in Paper IV) this may particularly apply when it comes to intuitive quantification of a type of numbers that we do not have much experience with. According to the findings above (and provided that their underlying assumptions are acceptable) there appears to be an underestimation of ecosystem damage by ReCiPe. As shown by Myllyviita et al. (2013), post-normalisation weighting by means of stated preferences such as that of ReCiPe does not really make any big difference: it is the normalisation that ultimately determines the results. And the term "normalisation" in this context is somewhat delusive: it does not anchor midpoint or endpoint indicators to anything "normal", but to a current level of ecosystem damage which is, by all accounts, unsustainable. If we implicitly use current societal *status quo* as a normative input to LCA, we should not expect LCA results to make any recommendation that can change the social, economic or technological order. The novel carrying-capacity based normalisation method of Bjørn and Hauschild (2015) appears to be more in line with the analyses and recommendations in this thesis. Notably, following the logic of Bjørn and Hauschild, the weighting/valuation/normalisation method presented in Supporting papers IV and V should be called normalisation. As also explained elsewhere, the value-laden character of the method in papers IV and V, and its departure from previous normalisation methods which normalised in relation to technosphere reference, instead prompted the use of the term weighting with no normalisation used, or "weighting/valuation".

Also, weighting that starts from normalisation would normally yield LCA results that indicate that all impact or damage categories are of some relevance. The results above, which in turn result from the observations in Papers I, II, IV and V, eventually mirror the sometimes observed societal attitude that global warming is a problem at a much larger scale than the other categories. This attitude is easy to understand from the findings of the article of Thomas et al. (2004) as well as IPCC (2007a), see section 1.1.2. This perceived wider range of differentiation by importance between environmental impact classes was also some of the driving force behind the initial development of CCS.

#### 4.7.4. THE POSSIBLE ROLE OF INDIVIDUAL "SOUL": RELATION TO DIFFERENT PERSPECTIVES ON INDIVIDUALISM

The weighting scheme assumes that the death of one person can be seamlessly replaced by the birth of a new person. This assumption may appear somewhat cynical, in the meaning rational. It considers humanity, ecosystems and resources as collective wholes, which does not allow the consideration of individual lifes or "souls". This is of course a very esoteric subject, but it is briefly discussed here nevertheless. It illustrates how the Problem of Regress discussed earlier in this document will always pose a lingering uncertainty to whether the "core essence" of a system has been identified or whether there is something perhaps more important that is still missing.

If one were to be individually [mortally] injured by environmental impacts, there is a chance that we would perceive it as relatively unhelpful or irrelevant in that context that another person to whom we might have no attachment or, perhaps, sympathy, is born at some random place on Earth. Or in other words, the proposed weighting scheme does not find any particular individual "soul" to have any more intrinsic value than another. Somehow, this implies a negation of the value of the individuality, the individual soul, of whoever is harmed by an environmental impact. Many of us probably have a feeling that our own individuality has immense value, and should not be replaced by anything else. How would this line of thought influence a weighting scheme?

Monotheist religions tend to consider time as linear, moving from a starting point to a final end. The "souls" of individual humans are thus never regenerated to the same form after death. From the perspective of an individual soul, then, regeneration time is undefined, or infinitely large. A weighting scheme based on regeneration time would thus be undefined, or alternatively, it would give human health infinite value as compared to resources and ecosystems.[13] The rejection of the latter, simple alternative is a prerequisite for investigating weighting factors instead of causal links towards human health damage. Provided that this is not obvious, it can be seen as a finding in this project.

Certain systems of knowledge do, however, consider individual souls as recurring. Some ancient Greek philosophers made claims about the time a soul resides in the death realm before returning to Earth through the process of reincarnation. If (perhaps) this time is added to the life length, it would yield the proposed cyclical regeneration time of an individual soul; it would thus be possible to compare to other possible safeguard subjects, although this would of course quickly become too esoteric to any science-related field. Majeed (2013) provides an overview of the historical and philosophical background, as well as different claims of the time different Greek philosophers claimed that a soul would reside before being reincarnated. This is summarised in table 9.

[13] Resources and ecosystems would thus only be assigned a value if they can be explicitly shown to provide value for the individual's life

*Table 9. The time given for a soul to be reborn/reincarnated, according to Majeed (2013), p. 127*

| Ancient Greek philosopher(s) | Time until reincarnation of individual soul |
|---|---|
| Empedocles | “not after” 30,000 years |
| Plato | 3,000 – 10,000 years (dialogue *Phaedrus*) |
| Later Pythagoreans; Stoics | 216 years |

If it were not conceived as far-fetched, these reincarnation times could be used in a weighting scheme, provided that individual, existing humans were considered a safeguard subject. Note that a Stoic would logically have more reason to be calm and relaxed than Plato: what they would not do in this life they could always do in the next. Also note that a strict adherence to the “regeneration time” weighting scheme logic in which the good of births “offsets” the evil of deaths would, logically, cause even more calm, particularly in a time where humans are plentiful and fertility rates are acceptably high. If any of this is regarded as relevant or potentially valid, it is also relevant that the Greeks in question did not consider souls to be exclusive to humans, or even to animals:

> *In Greek eschatology the soul was not believed to inhabit only human bodies. There was, therefore, belief in the transmigration of souls. In Orphic religion, for instance, the soul was believed to inhabit “successively animal and vegetable bodies” (...). Pythagoras seemed to have adopted this philosophy in addition to the very Orphic idea of the immortality of the human soul. For instance, Porphyrius reports Pythagoras as also believing that the soul could change into other nonhuman forms (Fragment 14, 8a).*

Science has not really concluded when it comes to “soul”; maybe it does not even exist. The general idea within biochemistry seems to be that consciousness (which may or may not be understood as equivalent to “soul”) emerges in parallel with extremely complex and intricate rearragements of microscopic and macroscopic matter, coordinated by among other things DNA, and these arrangements are lost forever after death. Hence, individuality or the hypothetical “individual soul” is never regenerated, and if it were considered a safeguard subject, it would thus be assigned infinite value. This is an atomistic explanation, and some philosophers might have objected to it by pointing out the possibility to perceive a “whole” even without any knowledge of microscopic details.

In brief, those who intuitively think that human health has been given too low weight in the proposed weighting scheme could logically have come to this conclusion by placing more emphasis on the value of the individual soul, and less emphasis on collective averages. Or, the weighting scheme described focuses on, and assumes, the *incarnation* of ostensibly newly created “souls” (or persons) rather than on the future or never-occurring *re-incarnation* of presently existing, individual “souls”. As implied in this section, the subtle difference between these choices can have large numerical implications.

Hence, basic assumptions causing the weighting factors deduced in this project could be at odds with influential philosophies. If an assumed sluggish or entirely lacking *re-incarnation* of valuable, currently living individuals is regarded as ubiquitous to the moral equation of weighting, other weighting factors that reflect this kind of “individualism” can be developed.

From the non-exhaustive treatment in this section, it can be assumed that the value of individuals’ human health is in significant dispute. Moreover, the proposed weighting set may understate the individual value of existing humans. From an objective point of view it must be recognised that the uniqueness of each human’s individual character has value, although particularly archetypical technocrats or grid-group hierarchists who find value in submission to systems and hierarchies, may disagree according to the archetypes (*sic*) of Douglas (2003).

Hence, individual value is probably something which each of us has to make a claim to, because it does not suit hierarchies and systems, and by extension LCA, to deal with individuality. This drawback with systems and systems thinking should be noted. There is likely not only a lower limit to how individualist-dominated and anarchistic one can allow a society to become, but also an upper limit to how much it is possible or ethical to ignore or curb individual differences. This criticism potentially applies to the stereotyping done in the estimates of LCA weighting/valuation. It is possible to imagine a society or societal contexts in which too many automated decisions are based on generic numerical weighted indicators or similar decision principles.

# CHAPTER 5. CONCLUSIONS

A calculation of LCA results involves an incorporation of immense amounts of diverse quantitative information. In the weighting step of LCA, all these very different pieces of data are expected to more or less magically fall into one place, thus allowing conclusions on total environmental performance to be reached. However, when one observes and understands but a fraction of the complexity and complications involved in this weighting process and the systems it tries to emulate or influence, it is tempting to slip into an anti-intellectual mode, and state that this decision process simply has to be surrendered to intuition, inspiration, chance or some form of higher power. Weighting discussions may end up as sophistry, and a too narrowly conceived weighting principle could eventually be given too much attention, which in turn could inappropriately remove attention from the big picture. Employing more than one weighting method might alleviate this problem as it may serve to highlight the uncertainty of each method, but every weighting scheme used should nevertheless be of acceptable quality.

As also emphasised in Paper V, placing blind trust in LCA weighting will predictably lead to poor decision-making. No number, however elaborate, should ever command an important decision on its own. Paradoxically, weighting is used for presenting environmental information in a quick and concise manner, but at the same time, in-depth knowledge about weighting as well as common sense, some form of "wisdom", are required in order to properly understand what this information actually communicates. Although weighting is quantitative, its adjacent qualitative discussions should not be lost out of sight.

Nevertheless, the project has managed to provide an answer to the research questions presented in section 1.2.3 in this document. To recapitulate, they are:

1. In general terms, which categories of facts are of higher rather than lower importance to LCA weighting? **Answer: Information construed at a higher level of generalisation can give more overarching and thus more useful information to a weighting/valuation methodology with a very broad scope (Supporting paper I)**
2. What is a high-quality weighting method according to LCA experts? **Answer: Supporting paper II provides a number of criteria for "good" weighting/valuation methods identified by an study of previously published LCA literature. One fashionable approach at the moment of writing appears to be "distance-to-sustainability target" approaches or methodologies based on references in the environment, as the method outlined in Supporting paper IV and V and by Bjørn and Hauschild (2015).**

3. What are the numerical priorities between different environmental impacts in the Arctic environment? **Answer: This is summarised by Supporting paper III, see tables 1 and 2 in Appendix C**.
4. In view of sustainability concerns, can a generally speaking "optimal" weighting methodology be identified? **Answer: Perhaps yes. The approach in Supporting papers IV and V was developed before the normalisation method of Bjørn and Hauschild (2015) was published, and the two approaches seem to converge towards some of the same ground. Further research on harmonisation of terminology (regarding weighting/valution/normalisation) is suggested in section 6.12 below.**
5. What is the set of weighting factors that can be derived from this weighting methodology? **Answer: This set is provided in the Supporting paper V. It is seemingly a matter of taste whether these factors can be called normalisation factors rather than weighting factors based on a fatalist value perspective.**
6. What are the implications for the environmental performance of CCS technology? **Answer: Ecosystem damage becomes by far the most important environmental issue for a natural gas-fired power plant with amine based post-combustion CCS, and ecosystem damage from climate change is by far the most important part of this. Provided that the weighting method is accepted as valid, electricity production with Modahl et al. (2012)'s CCS-3 scenario causes significantly less potential environmental insult than electricity production with the reference scenario without CCS. However, use of amine-based post-combustion CCS in a gas-fired power plant does not eliminate the environmental impacts. Applying the identified Arctic scaling factors will only cause less significant change to the numbers and does not change these conclusions.**

Papers III and V present regional scaling factors for the Arctic and an endpoint weighting set (for the case of no prior normalisation), respectively. Papers I, II and IV provide current weighting research with observations, discussions and findings which move to the core of the subject. Whereas the amount of empirical data which has been gathered during this project is perhaps somewhat limited, the methodological discussions as well as the scope which has been covered have been quite wide-ranging.

The project's findings within the wider context of LCA appear to have succeeded in defining the vague term of sustainability, at least in very general terms: it shows, or at least suggests, how the total environment comes together numerically.

The following bullet points repeat some of the same points in a slightly more detailed version:

- Paper V presents the generic weighting factors, and thus answers *Research question 5*. Paper III presents Arctic scaling factors, and thus answers *Research question 3*. Chapter 3 in this document presents the CCS case, and thus answers *Research question 6*
- These conclusions were reached on the basis of a literature survey of expert opinions on LCA weighting, Paper II, which in full answers *Research question 2*
- A preliminary answer to *Research question 1* was answered first by Paper I, and then further developed by Papers II, III, IV and V
- *Research question 4* was answered by Paper IV, in which regeneration time or regeneration period of a safeguard subject was recommended as a "quasi-objective" principle for weighting
- The weighting factors of Paper V places a much higher emphasis on global warming damage to ecosystems than other current weighting approaches. The discrepancy is explained by the larger degree to which other weighting schemes rely on existing societal practice, implicitly or explicitly
- The Arctic scaling factors of Paper III can be multiplied with corresponding weighted indicators/scores in order to pragmatically increase relevance to the Arctic region. However, these scaling factors should be regarded as preliminary. Perhaps importantly, Paper IV argues that intuitive "guesstimates" can ultimately lead to an underestimation of the numerical range of the weighting factor set. Nevertheless, this conservative approach to regional adjustment might help retain required inter-regional fairness and equality. Due to its overall particularities the Arctic environment should not be approached in a reductionist manner, *i.e.* with a primary focus on adjustment of details in LCIA models without an eye on the whole picture
- Provided the methodology and LCI results of Modahl et al. (2012), ReCiPe 2008 LCIA characterisation and the site-generic weighting factors of Paper V, and all assumptions and simplifications inherent to these, a natural gas-fired power plant with amine based post-combustion CCS and process integration ("CCS-3") causes less environmental insult than a similar power plants without CCS. The scenario of building an amine-based natural gas plant with CCS also causes harm to the environment, but to a lesser degree. The case of fitting a CCS module to an existing power plant (or to a gas-fired power plant that will be built no matter what) has not been investigated; this might be good for the environment. The answer to a potential question of whether "CCS is good" thus depends on the decision

context. Points of reference for "LCA of CCS results" should be thoroughly scrutinised: differing benchmarks may eventually foretell both that "CCS is bad" and that "CCS is good". Rebound effects as well as assessments of toxicity and cumulative future storage leakage are key omissions in most LCAs of CCS

- For both the cases in chapter 3, ecosystem damage and to a lesser extent global warming could be used as a proxy for the total damage inflicted without much error. This could be valid also for other LCA cases
- LCIA weighting methods should not be designed with the prior intention of assigning significant weight to every impact or damage category in most LCA results. As indicated by the weighting factors, if sustainability is taken in its literal sense, it may give recommendations that deviate strongly from commonplace environmental priorities and corresponding societal practices. A certain amount of courage is thus required from LCA practitioners who choose to forward such recommendations in a transparent manner
- Paper I provides an overview of at least part of the process over the course of the project. General information in the form of reviews, generic questionnaires, overarching (or fundamental) Earth principles and broad estimates of key aspects within very basic and general systems were important ideas during the process

*Key underlying pieces of data* are provided by (1) Thomas et al. (2004) and IPCC (2007a), who project that approximately 50% of global species would go extinct from unmitigated global warming in this century alone (*i.e.* about 50,000 a year)[14], and (2) the assumption that it takes approximately 1-10 years for the Earth system to reverse the loss of one species (*i.e.* about 0.2 a year). It should be noted that the estimate of IPCC (2007a), the Fourth Assessment Report, was not included in IPCC's Fifth Assessment Report, possibly because it was considered a relatively weak estimate.

Due to the fundamental importance of these estimates, the reader is encouraged to independently question to which extent these pieces of data are (a) relevant, and (b) valid. The reader may also feel free to imagine a society where these dimensions are fully acknowledged in decision-making. How would it look? Would such a society be desirable?

A myriad of other questions about the relation between this project and its possible societal implementation can be asked. Is forced sumbission to a common good acceptable, and if yes, under which conditions and circumstances? Must all acceptance of the common good be voluntary or explicit, and if yes, would anyone

[14] This piece of data is inherited from the global warming characterisation of ReCiPe 2008

want to sacrifice their personal health for the wider environment, and to the extent required? Or is the idea of an environmental trade-off as suggested in LCA weighting misplaced – can environmental protection perhaps create positive synergies and win-win scenarios? If so, how and under what conditions?

Chapter 6 will present possible improvements and perspectives for future research.

# CHAPTER 6. PERSPECTIVES FOR FUTURE RESEARCH

## 6.1. THE SUM OF CONTEXTUAL VALUES

It has been shown that the perspective inherent to the weighting scheme may contain elements of *fatalist* and *hierarchist* perspectives, while also subordinating individual incidents to statistics in a "collectivist" manner. It can be observed that stereotypical and possibly ruthless trade-offs and interpolations had to be made in order to reach a final, concise result. Paper I identified this as a possible weakness, but nevertheless a basic requirement for weighting. This general point was outlined in section 4.7.4.

From an individualist worldview, and also from the point of view of a collective of individuals, this form of weighting can be questionable. This perspective would insist that each existing human individual has immense intrinsic value. In a statistical treatment where one person is immediately substitutable for another, this intrinsic value disappears out of sight; it is considered redundant. The real sum of the value of such "redundancy" may, however, well exceed any "budget constraint" suggested by Weidema (2009) or other limits to growth. Another way to put this is that willingness-to-pay studies conducted from a high level of construal may yield a vastly different cumulative value of existing humans than that observed from a lower, more detailed level of construal.

A willingness-to-pay study of the (lost) value of one human life year from a very low level of construal might choose to, for instance, count and sum the value of every moment of every day in a person's life. The cumulative value of one year would thus become a minimum value of a disability-adjusted life year, DALY. It is not clear whether such a perspective is covered by the weighting scheme of Papers IV and V, and whether it would allow weighting to take place at all. The role of lost value seen from a low level of construal could be investigated by future research. One possible starting point is to identify limits to positivism and quantitative measures. This can involve analysis of Pythagoreanism, the Problem of universals, theory of science, and the *positivismusstreit*. Statistical analyses of people understate, or do not examine at all, the value of the individual character of each person. This is, however, also valid for statistical data of animals, forests, rivers and plants. A likely, recurring bias is that we tend to recognise more individuality in what and whom we know better. The proposed weighting scheme is not an attempt to negate or deny the value of individual character, but rather to counter any current cruel destruction of distant subjects which follows from this bias.

In connection to this, if willingness-to-pay studies are supposed to provide a full monetisation of the environmental damage, perhaps it would have to also take into account the unwillingness to involved in the breach of moral rules (cf. rule ethics). When damage to safeguard subjects is construed at a concrete, individual and personal level (and without any humour) the perceived value of avoidance costs could increase dramatically, as outlined in Paper I. Environmental damage can be regarded as a form of euphemised murder, and it is, after all, the role of LCA to uncover and show what actually happens. So what happens when the "distanced" language is removed? Future willingness-to-pay studies could try to take into account this "low level of construal". One can perhaps not fully measure grimness without a willingness to bluntly observe tragic outcomes. Perhaps it is *the sum of inflicted environmental impact and damage*, and not as proposed by Weidema (2009), our ability to assign a high value to safeguard subjects, that must be limited by a limit or budget constraint. The consequences of the willingness to at any cost *avoid emotion* in the publication of LCA studies and environmental research at large can be further investigated; construal level theory and Paper I could be possible starting points.

In sum:

- It may be further investigated to which extent the level of construal impacts valuation/weighting, and whether weighting can be performed at all from an "individualist" or even "egalitarianist" perspective as defined by Douglas (1973/1996)
- The effect that psychological distance in LCA has on eventual decisions, as well as potential countermeasures to this, can be explored
- In general, the relation between virtue ethics and "temperate" estimates which was hinted at in Paper I can be given more attention

## 6.2. DEGROWTH VS. LCA WEIGHTING

Performing an LCA rests on a fundamental assumption: that inflicting the environmental impact and damage eventually surveyed is actually an alternative. As highlighted in Paper V, a degrowth perspective could dismiss that such impact and damage needs to be examined in the first place. For instance, in the comparison of power plants based on different energy technologies, the alternative of not building a power plant at all can also be examined. As not doing anything or even removing power plants would often be seen as a sin of omission when a decision process has come to the assessment stage, investigating whether this is actually true or not would often be of interest. In order to improve the (future) environmental relevance of LCA, the "consequential" rebound effects (see above and *e.g.* Hertwich 2005) of the degrowth alternative should perhaps be given more consistent attention. For the case of energy technologies (including those with CCS) a choice of not building a power plant and thus not increasing power production capacity may have complex consequences – for instance, if certain newer mitigation technologies are not implemented in businesses due to this, it might to some extent also lead to environmental damage.

- How to develop LCA results for energy technologies (such as power plants with CCS) that somehow takes into account or benchmarks in relation to degrowth (or the alternative of doing nothing) should be investigated by future research.

## 6.3. CONSISTENCY CONCERNS: THE LEVEL OF PRECAUTION AND THE POSITIVE SIDES OF A PRODUCT

For the case of gas-fired power plants with CCS, the decision of whether or not it should be implemented may simply depend on one's focus on global warming. As explained, when it comes to global warming, panic may well be a viable alternative, because the problem is of an existential nature, unsolved and seemingly not about to be solved.

For the comparison between human toxicity and global warming, it has to be investigated whether the level of precaution is comparable in the impact and damage characterisation. Toxicity modelling in some cases rests on the precautionary principle and worst-case, whereas the climate models of IPCC is based on allegedly realistic estimates and scenarios. If the level of precaution is not equal for all characterisation modelling pathways, then this will skew the results.

In addition, products produced by humans do not only have negative consequences. Their eventual effect may often be to improve human health. For instance, growing food gives a number of environmental side-effects, but the main effect is that of food production, which is good for humans. As LCAs do not cover this full picture, endpoint results may become systematically misleading. As the functional unit produced normally favours present-day humans, but not ecosystems nor future generations, the value of (present) human health damage category may – in the broader view suggested – be likely to become consistently and systematically overvalued.

On the basis of this, there is a need to improve the consistency of LCIA. In sum, this amounts to two recommendations for further research:

- An analysis of whether precaution is consistently applied across LCIA categories
- An investigation of whether human health damage could be systematically overvalued by LCA due to an average positive effect on human health from functional units produced

## 6.4. WEIGHTING: "SCIENTIFICALLY PAINSTAKING" OR SUPERFICIAL AND NAÏVE? LESSONS LEARNT FOR PARTICIPATORY APPROACHES TO WEIGHTING

Michel Foucault (1968) claimed that "*a political thought can be politically correct only if it is scientifically painstaking*" ('politically correct' was apparently in this context intended to be interpreted literally, not ironically). As weighting to an extent is normative, it is perhaps also correct to label it "political". Some form of the same point is stated by Einstein (1952/1961), in the preface of his non-technical introduction to relativity:

> *I adhered scrupulously to the precept of that brilliant theoretical physicist L. Boltzmann, according to whom matters of elegance ought to be left to the tailor and to the cobbler.*

Whereas the Supporting papers and this document were indeed painstaking to develop, end results in e.g. chapter 5 of this document and Supporting paper V are nevertheless easy to understand. In fact, model design by means of modules (the weighting step is one such module), where each module has one easy-to-understand function, was suggested in Paper IV to be an advantage, as transparency was identified as an important criterion for weighting in Paper II.

The scaling factors of Paper III were developed from surveys, and the endpoint weighting factors in Paper V refer to "objective" (as in not subjective, not as in uncontroversial) empirical data. While the *background* of LCA weighting is very intricate, the weighting factors themselves do not require "scientifically painstaking" work in order to be understood. In reality, LCA weighting is a somewhat naïve exercise, as it assumes that sustainability decisions can be summed up by only a small, but concise set of linear factors. In order to fully understand the factors, however, their background and fundament needs to be thoroughly understood, and this is indeed painstaking work. Hence, yes, weighting is naïve, but only on the surface. If we dig below the surface of the topic, there is no overt lack of complexity.

The point of Foucault was possibly that *conclusions* should be so intricate and, indeed, opaque, that one can understand absolutely nothing of them without further in-depth study. (This would be the opposite of the transparency ideal recommended in Paper II and in functional systems design). If this is the ideal, weighting is indeed politically incorrect, as it seemingly can communicate (if not perfectly) both to the superficially-minded and to those who want to delve into all the philosophical and technical details. Note again that clarity at the superficial level is potentially dangerous, as it allows weighting factors to be applied without further criticism, as if they constitute readymade decisions or orders. As a remedy, Papers I, III, IV and V warn against placing too much trust in weighting factors.

Kørnøv and Thissen (2000) write, for the case of Strategic Environmental Assessment (SEA),

> *Most of the work in SEA seems to be based on the assumption that the provision of rational information will help improve decision-making, but the literature points to other characteristics of real decision-making processes*

A participatory approach is one way to make the decision-making less centralised and "naïve" in the sense discussed above. The question remains, however, whether decentralised and participatory approaches are ultimately capable of identifying and applying key issues, or whether they are likely to trail into more peripheral concerns. *If* the latter turns out to be an obvious problem, the following can perhaps be recommended on basis of this project:

- Apply current knowledge (Paper III), identify challenges and improve current knowledge (Papers IV and V)
- Question "why", particularly in the earlier stages of the inquiry (Paper I)
- Concisely summarise what scholars previously have said on the issue (Paper II)
- Understand that people have different perspectives (Paper IV); but nevertheless try to transcend differences (Paper IV)
- Try to identify, understand and numerically summarise relevant complex systems (Papers IV and V)

The alternative to a participatory or "egalitarian" approach is to submit to principles or "orders" from what is identified as a higher hierarchy, whether this be in the form of principles or dynamics identified within nature, scholarly authority, or some metaphysically conceived idea or cause. This implies, however, an acceptance of some sort of hierarchy of information, people or ideas. Paper I has attempted to outline one such hierarchy. Papers II and III assume that researchers are authorities with regard to LCA weighting due to their factual knowledge. Paper IV outlines how a particular kind of appeal to hierarchies is consistent with the concept of transcendence in peace research, as well as a fatalist (or alternatively hierarchist) perspective, as defined by grid-group typology. According to this typology, fatalism is the exact opposite of egalitarianism (although the choice of terminology (labels) in grid-group typology may be questioned). Participatory approaches are almost by definition anti-hierarchical, but nevertheless ought to acknowledge that hierarchies exist and can provide useful information. Otherwise, there would remain insufficient firm ground for any debate. To some extent, this appears to require competent mediation between perspectives, from a transcendent perspective.

The main trick when organising participatory research is thus to forward, but nevertheless not become fully and uncritically subsumed into participation, but to retain certain principles. Perhaps in contrast with science's and "democratic" approaches' claims to full veracity and transparency, this requires a certain amount of stylisation or dramatisation, a phenomenon which by design involves benign deception and an absence of full opaqueness.

## 6.5. FURTHER DEVELOPMENT OF ARCTIC CHARACTERISATION MODELS

The observations and findings of Paper III can be used as a starting point or road map for future development of Arctic-specific characterisation pathways in LCA.

- An investigation of whether or not *every* increase in environmental impact/damage in the Arctic must simply be dismissed as impossible or not recommended by the equivalent of a weighting step
- Improved detailed impact and damage characterisation, in accordance with the paper's observations on emissions and impacts of particular importance
- For the LCI modelling or goal and scope phase of an LCA, the inclusion of all emissions that may be particularly adverse in Arctic conditions, *e.g.* mercury, POPs and black carbon
- A particular focus on developing relevant pathways for ecosystem damage

## 6.6. LCA OF CCS: "THINKING OUTSIDE THE BOX" IN FUTURE RESEARCH

Further comprehensive calculations and analyses of the case similar to those of chapter 3 can relatively easily be performed provided access to the full LCI results of a comprehensive CCS-related LCA study and an integration of the factors developed in this project in computer tools such as Simapro. Comparing weighted results with energy production from renewables, nuclear energy, de-growth scenarios and other future alternatives would obviously be interesting.

The focus in future LCA studies of CCS should probably not be to model every technical detail with an ever-improved accuracy, but to think outside the box and try to find fundamentally new causal links that can illuminate the case from a new angle. In sum,

- Further research on LCA of CCS should preferably aim for innovation, not on improving small details within existing frameworks. As recommended in Paper II, there should ideally be more focus on what is relevant to the environment than on what is practical to the scientist,

- By extension, rebound effects of increased power production (and for the case of EOR, oil availability), toxicity, as well as projected storage leakage scenarios from CCS storage facilities should be consistently included in future LCA studies of CCS.

## 6.7. CONSISTENCY IN LCA GLOBAL WARMING DAMAGE CHARACTERISATION

As demonstrated by the CCS case, it is of vital general importance to LCA that damage characterisation of global warming follows the best available estimates. ReCiPe 2008 is based on Thomas et al. (2004), which does not significantly disagree with IPCC's *Fourth Assessment Report* from 2007. Note, however, that the *Fifth Assessment Report*, unlike its predecessor, has avoided suggesting an estimate.

Also, older LCIA characterisation methods that have not progressed to include estimates similar to those of Thomas et al. (2004) or similar studies in damage characterisation from global warming, are arguably by now obsolete. For instance, although the EPS2000 method has obvious merits when it comes to resource assessment (which *could* be assigned very high weight, viz. Paper V), it assigns species extinctions almost no significance even for the reference scenario of Modahl et al. (2012: their figure 4) which was analysed in the above. In view of the article of Thomas et al. (2004), cf. section 1.1.2, as well as the case investigated in this project, this either does not make much sense, or alternatively it suggests that resource depletion has an extremely high damage potential.

Furthermore, in view of recent standardisation efforts such as that documented by Hauschild et al. (2013), it is perhaps time to evaluate whether older and by now lacking LCIA methods should be removed from or tagged with a warning in LCA software packages, or somehow partially merged with other methods. LCA practitioners do not always have sufficient knowledge to be able to make such priorities on their own. Also, due to the importance of this topic, additional and/or updated characterisation pathways related to ecosystem damage from climate change should be continuously developed. In addition, future research might want to investigate the problem of causal interconnectedness between the damage categories which is pointed out in Paper V.

Whereas IPCC (2007a) provides a comprehensive review of the scientific state of the art on extinction risk from global warming, this is a key issue which calls for even more research and attention. The methodology of Thomas et al. is somewhat simple, and it can be observed that since 1750, according to IPCC (2013, p. 10):

> *Of these cumulative anthropogenic $CO_2$ emissions, 240 [230 to 250] GtC have accumulated in the atmosphere, 155 [125 to 185] GtC have been taken*

*up by the ocean and 160 [70 to 250] GtC have accumulated in natural terrestrial ecosystems (i.e., the cumulative residual land sink).*

There may (or may not: the quote refers to the past, not the future) be a trade-off involved between IPCC's (previously) projected biodiversity loss and possible biosphere gain from increased carbon availability which is not currently taken into account by ReCiPe 2008's damage characterisation (*cf.* the level of detail of Lindeijer et al. 2001). In general, as the characterisation of damage to ecosystems from global warming is a key issue, it should be given corresponding and sufficient attention by LCIA researchers.

## 6.8. ECONOMIC GROWTH AS AN EFFECT OF RESOURCE DEPLETION

From a more general perspective, the findings of Paper V seem to suggest that observed economic growth could be an effect of resource depletion: we work more because resources are less readily available. Perhaps the validity of this idea, and its possible policy implications, could be investigated further.

The weighting method of Paper V can furthermore more explicitly be developed into a valuation method. Note that the regeneration-based weight of resource depletion and the similar weight of "damage to trade transactions/contracts" (if such transactions are accepted a safeguard subject in a future valuation method) will not necessarily be the same. This can all perhaps be explored in an article.

## 6.9. ESTIMATES AND "GUESSTIMATES"

A basic tenet of the project is to take a second look at any weighting or valuation method which can be thought to be fundamentally based on "guesstimates", or at the very least to not rely exclusively on such weighting methods. Such quantification is not based on any *explicit* argument(s) or principle(s), and it is therefore difficult to know whether they are based on something of great substance or on thin air. Perhaps we tend to underestimate the importance of and the current scale of damage to what we do not see in our everyday life, such as ecosystems, and perhaps particularly underwater life. Nevertheless, future research should look into how to cope with and minimise such ignorance, as well as framing concerns, in weighting surveys so that people can voice their opinion. It does not currently seem like a risk that sustainability-based weighting/valuation/normalisation will become too monolithic and dominant in decision contexts, but if the current development continues, with e.g. Bjørn and Hauschild (2015) and the contributions of the current project, this can change, and one may suddenly feel the need to scramble to revisit more societal perspectives again. Solving the most pressing problems with these methods is therefore of continuous importance. One possible starting point is to revisit the book *Memoirs of Extraordinary Popular Delusions and the Madness of Crowds* (Mackay 1852/2008).

## 6.10. UNIT OF “REGENERATION TIME” WEIGHTED INDICATOR

The unit of the regeneration time weighted indicator is time squared. The unit time squared is not easy to interpret. Although the ancient Greeks originally divided time into two dimensions, chronos and kairos (Rämö 1999), most “rational” Westerners today hold time to be one-dimensional. This is antithetical to the Aboriginal Australian notion of *dreamtime* and its associated totemism. Totemism is not “rational”, and fits awkwardly into a PhD project which relates to an engineering subject, but more often than not relates more or less directly to mediation between ecosystems and human affairs, which in the introduction was shown or chosen to be relevant to weighting. Isaac Newton, in his *Philosophiæ Naturalis Principia Mathematica* (Newton 1729, p. 9) also distinguishes between two classes of time:

> *I do not define Time, Space, Place and Motion, as being well known to all. Only I must observe, that the vulgar conceive those quantities under no other notions but from the relation they bear to sensible objects. And thence arise certain prejudices, for the removing of which, it will be convenient to distinguish them into Absolute and Relative, True and Apparent, Mathematical and Common.*

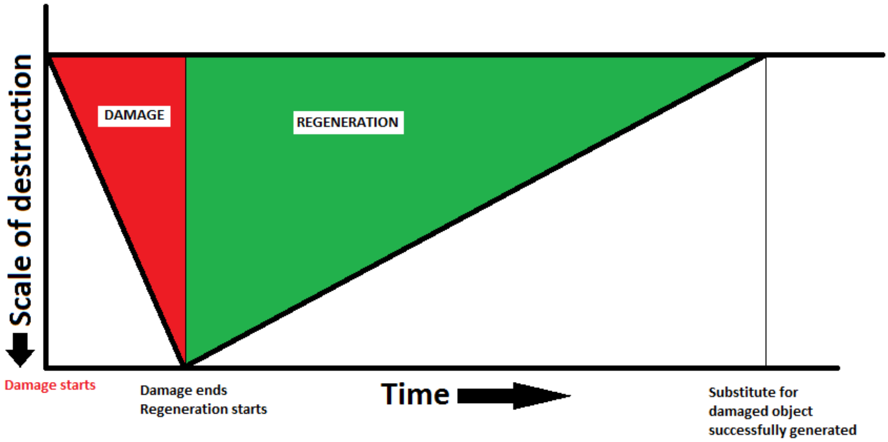
In practice, however, the emergence of the time squared unit is less mysterious than it would seem: it is an artefact of the structure of endpoint-based LCIA, in which damage characterisation is seen as entirely separate from weighting. Simple multiplication of very comprehensive estimates/indicators is a relatively primitive form of mathematical modelling; it assumes perfect, direct proportionality and no entanglement between, in this case, damage characterisation and endpoint weighting. There is, however, possibly a dependency between the time dimension used in damage characterisation, and the time dimension used in endpoint weighting. Provided that only one time dimension exists, seemingly the best way to mathematically merge two distinct time-dependent dimensions is by reducing the treatment of time to simple addition and subtraction, thus avoiding exponentials of time. For our case, this would mean that damage characterisation and endpoint weighting should be incorporated into one step. This would most easily be done by integrating damage characterisation and “regeneration weighting” as described in the following. The meaning of the final unit of the weighted indicator can then be further analysed by future research.

If the regeneration time of the damaged item is a viable weighting principle, future research might want to integrate it with the damage characterisation, in order to characterise a “full damage”:

> Full Damage phase = Destruction phase + Reconstruction phase
>
> Destruction – what is currently analysed by the damage characterisation step: “Damage”

Reconstruction – what is currently analysed by the weighting factors of Supporting paper V

This allows the time dimension to avoid being squared, by instead employing integration of the instantaneous *level* of destruction in relation to initial level, over time. The area indicated in figure 11 (green + red) would denote "not substitutable loss" due to LCI results/calculated environmental impacts (functional unit).




## Figure 10. Damage and regeneration, plotted onto the same time axis

Note that whereas the diagram is a common sense representation of the damage-regeneration process, it does not represent what actually takes place mathematically in the project. Due to the module-based nature of LCA, the respective time dimensions of damage and regeneration is modelled as perpendicular, not parallel. This is the only available assumption when characterisation and weighting factors are regarded as independent, as LCA standards prescribe, but it may appear somewhat confusing that time, which only exists one-dimensionally in reality, can appear as two-dimensional in the model. The idea behind this is that both damage and regeneration have particular temporal attributes, which both are assumed to be directly proportional to the weighted score. This is somewhat simplistic, and a difficuilty which arises by reducing damage characterisation and endpoint weighting to mere factors. A possible remedy is to model the dependence between damage and generation, although this would introduce more complexity.

Another possibility for further research is to argue that regeneration is a "grave-to-cradle" approach, and that with its addition LCIA can provide not only a "cradle-to-grave" assessment of damage, but a full cyclical life → death → life "cradle-to-cradle" assessment also in the LCIA module.

This idea is quite intriguing, but also ambitious and will require a large degree of generalisation and probably somewhat sweeping assumptions. Let us also remember the potential metaphysical difficulty to such efforts hinted at by the peculiar table 9 above. It is not necessarily a law of nature that everything in the universe will be possible to fit into a module-based structure such as LCA.

## 6.11. RELATION TO OTHER APPROACHES

The regeneration weighting/valuation approach is similar, but also complementary to the approach of Bjørn and Hauschild (2015), which considers abrupt transgression of thresholds as the key environmental problem, as opposed to the gradual and continuous removal from steady-state which tacitly was identified as the key environmental problem in Papers IV and V. Due to their contemplarity, it would perhaps be possible to somehow integrate the two approaches.

The approach can possibly also be linked to the distance-to-target weighting sets developed by Castellani et al. (2016).

## 6.12. TERMINOLOGY ISSUES

There may also be further need to harmonise the use of "normalisation", "weighting" and "valuation". An article by Pizzol et al. (2016) suggests a taxonomy for solving this issue, but it does not take into account that both the approaches of Bjørn and Hauschild (2015) and the approach developed in Paper IV and V can (at least in the view of this author) be understood as hybrid approaches and that there are arguments for placing them in each of the three categories. Notably, both focus on somewhat objective dimensions (characteristic for normalisation according to ISO (2006)), but at the same time both argue that they can be used to calculate an aggregated environmental score (characteristic for weighting according to ISO (2006)).

It is perhaps time to reconsider the strict division between normalisation and weighting in ISO (2006), where no middle ground is allowed. One key underlying problem is that the definitions of "objective" and "subjective" are not obvious; what they mean is in contention between different academic disciplines, within the theory of science, in philosophy, etc. Perhaps it can be argued that approaches which can be argued to belong both in the normalisation and weighting category should simply be called "valuation" approaches. These are perhaps discernable by the property that they do not really require either weighting after normalisation as the approach of Bjørn and Hauschild (2015) or normalisation before weighting as the approach developed here.

Perhaps this ambivalence also applies to some approaches that can be classified as "distance-to-target" (Castellani et al. 2016). All of this is up to future research and discussion to decide, however.

## 6.13. GENERAL OUTLOOK

For the case of environmental research in general, more attention could be directed to ecosystem damage. It might be time to rejuvenate innovation with the same profound scope and fundamental questioning of conventions as the deep ecology of Næss (1973): for instance, to direct much more research attention towards both realistic and idealised degrowth scenarios (Nørgaard 2013). Future prevention of waste and environmental impact cannot all be based on assumed technological innovation; genuine societal innovation is also needed. Any research approach which does not, implicitly or explicitly and at least to some extent, take the gravity of the current environmental situation into account, runs the risk of proving misguided. In addition, science journalism in its current form tends to be ineffective. This in turn highlights a need to create new platforms for communication. Academia may need to be a catalyst in such processes: the accuracy of empirical studies is indispensable, but it needs to be amalgamated with foresight, experience and innovation, and complemented by implementation and action (*e.g.* Arendt 1958/1998; Susman and Evered 1978). One lesson learnt from this project is that it may pay off to question *frames*: never be enclosed and essentially imprisoned by unhelpful frames. Moreover, there is probably no such thing as no frames – notably, the requirements for acceptable academic or scientific writing, such as this thesis, apparently rests on something, not nothing. Any scientific method assumes that authors eventually manage to reach sufficient eloquence – but what is the cause of it, and how and where can friends of the total environment harvest this source?

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This project has uncovered a few partial truths about sustainability: The relation between the respective slowness of certain vital cycles is a factor which needs to be recognised before damaging the environment. Of course, non-cyclical elements can also be subject to damage, and they may prove to be elements that should also be accounted for.

Finally, it should be noted that there are many ways of assessing the imporance of different environmental impacts. It is not unlikely that the next individual to dig into a similar subject-matter will recover a completely different way of trading off environmental impacts than this project. It is probably better to understand the results as propositions, although hopefully valuable propositions, than to regard them as rigid scientific truths that cannot be questioned or improved.

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